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THESIS

A DETERMINATION OF THE RISK OF INTENTIONAL AND UNINTENTIONAL ELECTROMAGNETIC RADIATION EMITTERS DEGRADING INSTALLED COMPONENTS IN CLOSED ELECTROMAGNETIC ENVIRONMENTS

by

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13. ABSTRACT (maximum 200 words)

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There is a constant desire to include new technology into the systems being designed to operate onboard U.S. Naval vessels. One of these technologies is wireless communications. This technology relies on the use of the electromagnetic spectrum in order to transfer information from one point to another. This type of information transfer can be advantageous in various applications.

Exposing sensitive electronic components to a time-varying electromagnetic field increases the risk of an electronic upset in those components that will degrade the functionality of installed systems. This risk determination should provide a way to weigh the risk of introducing wireless technologies in enclosed spaces.

This risk determination relies on the assumption that at some point there will be enough data collected to properly determine the overall risk to at-risk equipment. Until that occurs, incorporating new methods of shielding and low power technologies is recommended.

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LIST OF ACRONYMS AND ABBREVIATIONS

AM	amplitude modulation
DOD	Department of Defense
DSM	dynamic spectrum management
EM	electromagnetic
EMC	electromagnetic compatibility
EMI	electromagnetic interference
FFBD	functional flow block diagram
FM	frequency modulation
LAN	local area network
LTB	larger the best
NTB	nominal the best
OOD	Officer of the Deck
SE	systems engineer
SORM	standard organization and regulations manual
STB	smaller the best
VLS	vertical launch system

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EXECUTIVE SUMMARY

Today, engineers utilize the physical properties of electromagnetic radiation in a multitude of ways to accomplish numerous tasks and functions at the speed of light. In the recent past, if someone wanted to access large amounts of specific information they would be required to locate themselves near some form of access terminal. Presently, this same task can be accomplished on a beach, on a plane, or on a plane while travelling to a beach thanks to wireless technologies and their ability to transfer information from one place to another using the electromagnetic spectrum.

While the benefits of wireless technology are self-evident, the risk of purposely radiating electromagnetic energy in an enclosed space with sensitive electronic components is a complicated matter. In most testing environments, there is a limited number of samples that can be taken and a limited number of experiments based on time and cost restrictions. Therefore, a deterministic approach to assessing risk is not feasible. Furthermore, the use of modelling and simulation at the current state of the art is only good enough to model a single component in a time varying electric field (ANSYS 2015). Accurately modelling an entire space full of sensitive electronic components in a time varying electric field is simply not possible. These facts indicate a need for a risk determination that can be integrated into the systems engineering process for assessing the effects of intentional and unintentional electromagnetic radiation emitters in the reverberant enclosed spaces typical of those found on U.S. Navy vessels.

The systems engineer is tasked with applying solutions to the problems they are assigned. These problems come in the form of stakeholder requirements that need to be evaluated to determine best possible system solution to accomplish the required tasks. Once the system functions are determined then the systems engineering team must perform a full functional analysis to ensure that there is an available resource to accomplish the given tasks in the problem statement (Blanchard and Fabrycky 2011).

This analysis may lead the systems engineering team to implementing wireless technology as a resource to fulfill a given function or functions. However, these

technologies may interfere with the installed components in a given space. This paper describes a method for improving understanding of the risk involved with these technologies being allowed to operate in enclosed spaces collocated with sensitive electronic components.

The first step of this method is a functional decomposition of each system within a given space to determine the interactions between components and then a functional mapping that applies these functions. This type of functional mapping is to determine which objects (electronic components at risk of interference) are the most critical to the system operation.

After the functional mapping is complete, it is used to accurately discover a measure of effectiveness that is well-framed and contains both well-defined boundaries and an integrative framework that identifies the domains for assessment (Langford 2014).

The risk determination proposed in this paper uses a loss function (Roy 1990) in conjunction with a Rayleigh distribution to develop a risk function that will give an engineering team a supplemental risk evaluation method that incorporates qualitative and quantitative information in order to facilitate the a more complete representation of the benefits in light of the possible consequences involved in wireless technologies.

The main limiter of this risk determination method is a lack of data. In order to fully understand risk using the proposed method in this paper and other risk models, it is necessary to acquire data on the effects of electromagnetic radiation on sensitive electronic equipment.

Until then it is recommended that the U.S. Navy continue to severely limit electromagnetic radiation emitting devices in sensitive enclosed spaces and possibly investigate novel approaches to component shielding and reducing the average power of installed wireless technologies using meshed networks.

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I. INTRODUCTION

A. INTRODUCTION TO ELECTROMAGNETIC RADIATION

1. Electromagnetic Radiation

The transfer of energy from one point to another was one of the most important developments in the past 150 years. The ability to generate an electrical potential in one location and then use that potential to induce the flow of electrons and therefore create heat, light or motion in another location was a major leap forward in the development of what is now known as the first world. The technology of connecting power source to power sink through miles of a flexible conductor has lit up a world.

Electromagnetic (EM) radiation is also a method of transferring energy. In 1864, James Clerk Maxwell combined the theories of Ampere's magnetic force and Faraday's electrostatic force. He postulated that in a circuit with alternating current and a capacitor that if there was current flow in the circuit then there must be what he termed a displacement current to account for current flow in the circuit even though there is a gap and no current actually flows through the capacitor. (Niknejad 2007). This meant that there was a smooth time varying relationship between the electrical field and the magnetic fields within the capacitor. As the electrical field increased, the magnetic field decreased, and as the electrical field collapsed, then the magnetic field would increase and this collapsing and rebuilding between the two fields in the circuit is what allowed for a potential voltage to develop in the second, unconnected, plate of the capacitor. (Niknejad 2007)

These fields are known as near fields. They are generated within the circuit components and do not leave the circuit or radiate away from the circuit (Scmitt 2002). While these fields are important when considering the effects on electrical components, it is the far field and its effects that will be focused on in this paper. The distances involved in determining whether an EM field is near or far can be seen in Figure 1.

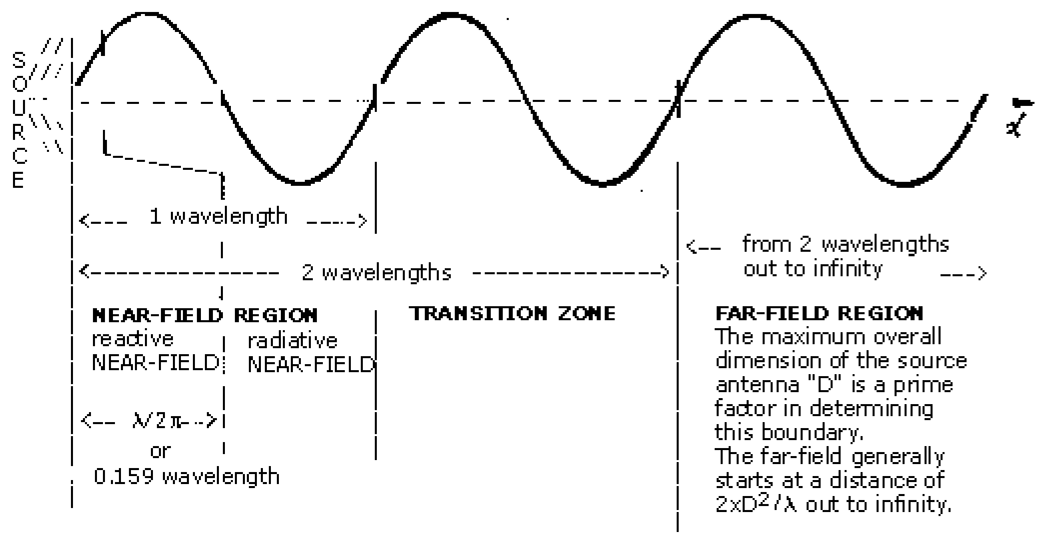

Figure 1. Antenna field regions for typical antennas (from OSHA 1990)

Far field electromagnetic (EM) radiation has many forms and is created or generated in many ways. The most recognized form of EM radiation is visible light, and again Maxwell was the scientist who purported that the radiated EM fields from his experiments traveled at the speed of light, and Heinrich Hertz that later proved that theory (Scmitt 2002). This indicates that there are waves of energy radiating away from a source such as an antenna that contains both electrical and magnetic components at the speed of light. These far fields travelled in waves. This is similar to the waves seen in physical medium such as in water when a pebble is dropped into it. There is a transfer of energy occurring without a lateral displacement of the matter as the wave passes through the matter in the material (OSHA 1990). This wave phenomenon can be described as shown in Figure 2.

The amplitude of the wave can be also regarded as the strength of the wave or the energy of the wave at a particular place in time and space. The frequency of the wave is the time it takes for a full cycle of the wave to occur. This can also be described as the wavelength of the wave if one measures the physical distance between two identical points in the wave’s cycle.

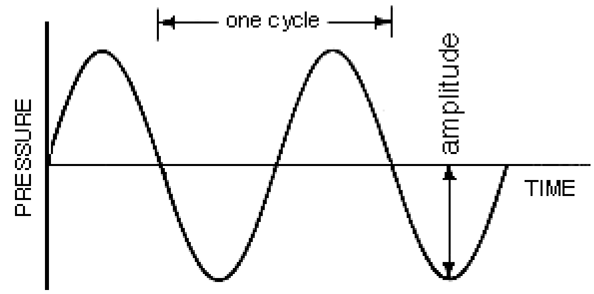

Figure 2. Wave characteristics (from Dalton 2015)

The frequency of the wave is measured in Hertz or cycles per second. The amplitude units for a wave depend on the wave and the medium in which it is travelling.

Electromagnetic radiation is defined by its frequency. For example, visible light is EM radiation that humans can detect with their eyes. The frequency of visible light is approximately 430–790 terahertz, which corresponds to a wavelength of approximately 390 to 700 nanometers (Berkeley Lab n.d.). As shown in Figure 3, this is a minor portion of the entire EM spectrum. With what is commonly referred to as “radio waves” at the low end of the spectrum at approximately 1000 Hz and gamma rays at the high end of the frequency spectrum at around 1×10^{20} Hz, one can see that the spectrum of EM radiation is much wider than just what the average human eye can detect unaided.

The relationship between the electric field (E) and the magnetic field (H) in EM radiation can be compared to a simple electric circuit. The electric field is similar to the potential of a circuit while the magnetic field resembles the current. (OSHA 1990) Although it is a mathematical oversimplification, the relationship $E = H \times 377$ in free space where 377 = the impedance of free space (a constant that is expressed in ohms) (OSHA 1990).

As EM radiation moves away from its source, it will interact with the environment, transferring energy to objects that it encounters. This rate of energy transfer is dependent on the power density (P_d) at the point of interaction.

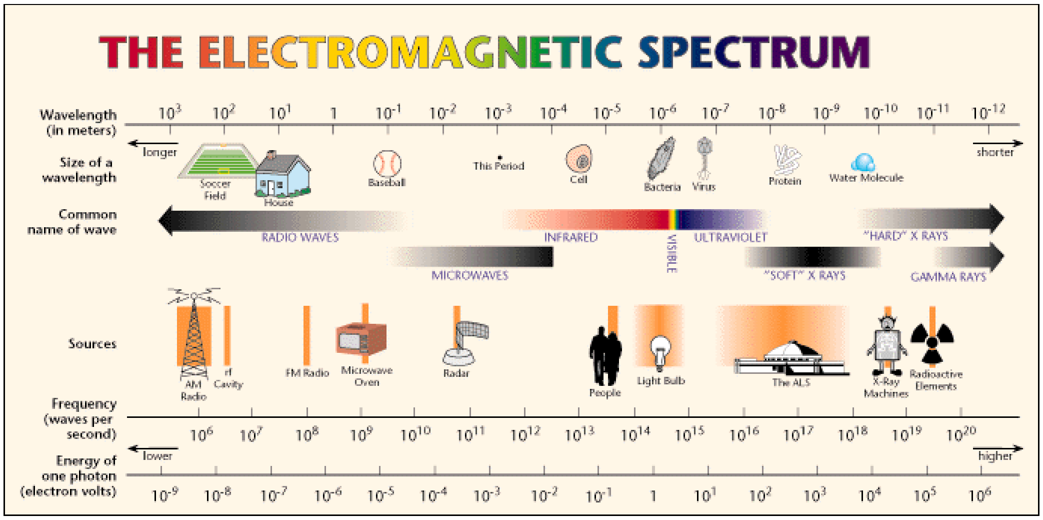

Figure 3. The EM Spectrum (from Berkeley Lab 2015)

Power density is the rate of energy transfer per unit area and is found with the following equation:

$$P_d = E \text{ (volts/meter)} \times H \text{ (amperes/meter)}$$

Therefore, the units for P_d are watts/meter^2 and if combined with the previously stated equation $E = H \times 377$ (OSHA 1990) one can determine the P_d by measuring only the electrical field at a given point and then determining the P_d instead of measuring both the electrical and magnetic fields. (OSHA 1990) The further away from the source the electric field is measured, the lower the measurement will be. This is because as the radiation moves away from the source in a spherical pattern it contains the same energy, spread over the surface of the ever-growing sphere. This energy loss is proportional to $1/r^2$ where r is the distance from the source or the radius of the sphere (Scmitt 2002). However, in enclosed spaces onboard U.S. Navy vessels where the walls, floor and ceiling are composed of mostly steel, the dissipation of EM radiation as a function of distance becomes a much more complicated calculation. It becomes necessary to include the effects of reflection and wave propagation. As discussed later in this paper, these calculations quickly become probabilistic in nature, and those probabilities will be used in the risk determination proposed.

2. Electronics in EMEs

a. Natural Sources of EM Radiation

There are two source categories of EM radiation. These categories are natural and manmade (Christopoulos 2007). Natural fields can be broken down further into the sub-categories of low-frequency electric and magnetic fields, lightning, and high-frequency fields (Christopoulos 2007).

The most well-known low-frequency EM field is the geomagnetic field which is the field generated by the Earth's dipole magnetics with the "north" geomagnetic pole being located in the northern reaches of Canada (Kitashirakawa-Oiwake 2015). The general strength of this field is relatively small, but in some cases, if the fields vary enough in a short period of time, they can create a potential difference in the Earth's crust and drive currents that have been measured as high as 100 amperes (Christopoulos 2007).

Lightning is another source of natural EM radiation. A detailed explanation of this phenomenon will not be discussed in this paper. However, it is important to note that lightning is a very severe threat to airplanes, and extensive testing has been done to protect the planes from damage caused by not only lightning strikes, but near misses as well (Christopoulos 2007).

The last natural source of EM radiation is high-frequency fields. Below 30 megahertz, most of the fields are generated by the Earth's electrical storms, but above the 30 megahertz, the fields are due to extraterrestrial sources (Christopoulos 2007). Fortunately, the Earth's atmosphere forms an EM shield that tends to lower the EM levels at the surface of the Earth (Christopoulos 2007). It is important to note for the purposes of this paper that the majority of the Earth's cosmic radiation is due to its proximity to the sun. While the normal levels of EM radiation from the sun are relatively low, during radio bursts (solar flares) on the surface of the sun, the energy levels can be increased by a factor of 1000 for hours at a time (Christopoulos 2007). These events can affect exoatmospheric satellites, including the International Space Station, and even some equipment at the surface of the Earth if the flares are strong enough and last for a period of time (Maximum 1998).

b. Manmade EM Radiation

This paper will focus exclusively on manmade EM radiation. This is due to the enclosed space focus of the risk determination being proposed. There are a multitude of sources of EM radiation that are in use today, and they all have a probability of affecting electronic components in their vicinity in some way.

The earliest forms of manmade EM radiators were radio transmitters. These are the signals used to broadcast information into homes and vehicles from long distances that are usually translated into audio signal, amplified and then into audible information that the human ear can interpret by a speaker. The United States Federal Communications Commission in accordance with 47 U.S. Code § 151 dictates what EM frequencies can be used for what applications within the United States. They also regulate the amplitude or power of the broadcasts in order to prevent overlap, which then creates issues of interference between the different users of the EM spectrum.

The first radios used by the public utilized amplitude modulation (AM) in order to send audio information in the form of an EM signal. The first thing needed for the signal is the carrier signal at a given frequency (Schnickel 2000). This signal is sent out at a specific frequency, in the United States, the general frequency band is 535 hertz to 1705 hertz (Guney 1994). Once the carrier frequency signal is established, a message signal is applied which adjusts the amplitude of the EM wave at the given frequency based on what information is being sent. (Schnickel 2000) The receiving unit interprets the changes in amplitude into an electrical signal that it sends out to the speaker magnets. Frequency modulation (FM) works in a similar manner except that instead of the message signal modulating the amplitude of the carrier signal, it modulates the frequency slightly and the receiver interprets these changes in frequency as information to send out to the speakers (Schnickel 2000). The differences between FM and AM radio transmission signals are shown in Figure 4.

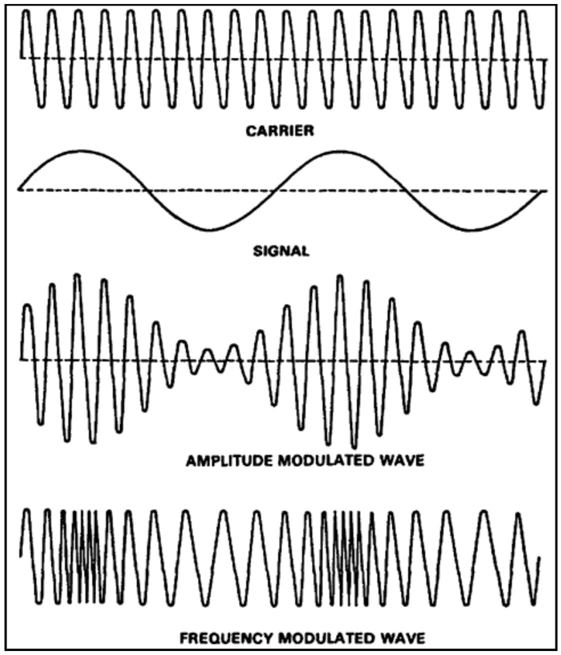

Figure 4. AM versus FM Signal Modulation (from Global Securtiy 2015)

EM energy can also be used to heat different materials through either induction or dielectric heating (Christopoulos 2007). Induction heating is used to heat materials that are conductive by applying EM radiation at frequencies of 1 to 100 kilohertz and 1 megahertz (Christopoulos 2007). Dielectric heaters, such as the microwave appliances in today's kitchens, operate at frequencies of 13.56 megahertz, 27.12 megahertz, 40.68 megahertz, 433 megahertz, 915 megahertz, 2.45 gigahertz, and 5.8 gigahertz (Christopoulos 2007). These appliances typically are not in enclosed spaces with sensitive electronics and will not be included in the scope of this thesis.

Another source of EM radiation is from power transmission, and will not be discussed in the scope of this thesis. While there is power transmission in the enclosed spaces of concern, they are not the focus of this thesis.

c. Effects of EM Radiation on Electronic Components

Using EM radiation as a method of communication between electronic devices is standard within the enclosed spaces of today's work environments. This includes the enclosed spaces of U.S. navy vessels. The need and/or desire to include these devices in onboard systems is no longer in question, but the effects must be studied intensively to

ensure the negative effects are well understood so that proper designs and safety concerns can be implemented. Even though the electronic components/systems of concern are complex in nature and the multitude of simultaneous interactions of an EM field with even a simple construct is difficult to model correctly, it is important to discuss the basic physical reactions within the circuit that actually cause deleterious and undesirable effects.

A complex circuit board can be broken down at the fundamental level to simply a straight line of conductive material. This conductive material can undergo many different processes simultaneously. It could have a voltage placed across it and therefore an electrical current will flow through the wire the level of which is dependent on the resistance (R) of the conductor (Kumar 2009). This effect is based on Ohm's law, which states that, "if the physical condition like, temperature, remains unchanged, then the current (I) flowing through a conductor is always proportional to the potential difference (V) across its two ends" (Kumar 2009). The mathematical equivalent of this law is $V = I \times R$. If there is no voltage applied to an electrical component then there is no current flow. However, there is more than one way to induce voltage. According to Michael Faraday and his Law of EM Induction, "A changing magnetic flux inside a loop made from a conductor material will induce a voltage in the loop" (Klempner 2011) It is this induced voltage and the resulting current that are affecting the electronic and electrical components of concern in a negative way as discussed earlier. The voltage induced in the conductor is directly proportional to the rate of change of the magnetic field (Klempner 2011). This means that the frequency and amplitude of the EM radiation at the receptor of concern correlates to the amount of electromagnetic interference (EMI) experienced by that component.

When considering the effects of EM radiation on electronic components, system designer need to understand any unwanted interaction between the radiation and component of concern as an EM disturbance or upset (Kodali 2001). This disturbance comes in the form of noise on the system, unwanted signals or a change to the signal itself as it interacts with the components (Kodali 2001). Electromagnetic interference is the degradation of performance or function of an electronic component caused by an EM

disturbance. There are two ways that electronic components experience EM disturbances: radiation and conduction (Kodali 2001).

There are two main components to consider in the simplest models of EMI. There is a source of EM radiation. This is typically an antenna that is designed to produce a specific frequency of EM radiation at a given average power level. The other component in this simple model is the receptor or victim. The receptor is the component that receives the EM radiation and is affected by it (Kodali 2001). There are a many ways that EMI can travel from the source to the receptor.

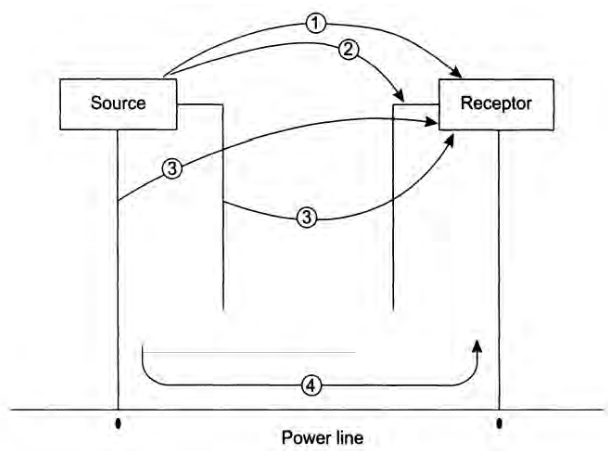

Figure 5. Mechanisms of Electromagnetic Interference (from Kodali 2001)

Figure 5 illustrates the four mechanisms of EMI. The first mechanism is direct radiation for the source to the receptor. The second mechanism is direct radiation form the source interacting with the electrical power or signal cables of the receptor and interfering with the receptor by conduction. The third mechanism is EM radiation generated by the sources' power and signal cables interacting with the receptor. The last mechanism occurs when both the source and the receptor use the same power lines or signal lines and EMI is conducted through these lines (Kodali 2001).

The focus of research on EMI in commercial applications is more concerned with ensuring signal integrity and reducing biological effects on its users (Kodali 2001). In today's military, and more specifically the enclosed spaces onboard U.S. Navy vessels

the major concern is the effects of EM radiation and EMI on sensitive integrated circuits (IC) that may affect anything from simple display equipment to elements that affect national security. In severe cases, EMI may cause these circuits to “burnout” or become non-operational (Kodali 2001). In circuits that utilize digital signals, EMI can cause increasing bit error rates or malfunctions in the circuit (Kodali 2001). With analog systems, the EMI increases the overall noise level on the circuit and this can prevent proper signal processing and operation of the circuit involved (Kodali). The specific negative effects of this phenomenon will be discussed later in this paper.

The use of wireless technologies in enclosed spaces does have some probability of causing negative effects as described above. However, they also bring extra level of functionality and utility that can be beneficial to a ship and her crew

B. BENEFITS OF WIRELESS COMMUNICATIONS

1. Introduction

In the U.S. Navy in the 1990s, there was a push for a “paperless Navy” (Harness 1997). This directive was put in place in order to save the U.S. Navy money and effort by completely eradicating the need for physical paperwork to be produced onboard ships and at shore commands. Even at the time of the directive’s issuance the idea of making every single thing the Navy does paperless seemed farfetched and out of reach for most of its internal organizations.

It is now 2015 and the U.S. Navy is not a paperless organization. There have been some advances in helping to reduce the paper production though. On July 27, 2010, the U.S. Navy officially announced implementation of its E-leave system (Howard 2010). This system removed the requirement to physically fill out a leave request chit and walk it around the command to different people to have them approve the chit manually by signing a piece of paper. Other similar programs include electronic service records and electronic mustering services like the one used at Naval Postgraduate School.

These services are based on using the Internet to help alleviate the need for paper purchasing and preservation in the U.S. Navy. With Wireless Local Area Networks (LANs) being implemented in the onboard environment on surface ships and submarines,

it is important to survey the possible gains from the technology to see where the U.S. Navy and its sailors can benefit.

2. Information Gathering

Each ship in the U.S. Navy is required by the Standard Organization and Regulations Manual, OPNAVINST 3120.32d, typically known as the SORM, to keep a ship's deck log. This is the "official daily record of a ship, by watches," and is a running record of all the major events onboard a ship. These logs are legal and historical in nature and are kept by the U.S. Navy indefinitely. This means that every ship that has ever been in the U.S. Navy retains every page of its daily happenings, boxes them up at the end of the month and sends them off to the Naval History and Heritage Command in Washington, D.C., They stay at this command for 30 years and are then transferred to the National Archives. This amount of information and paperwork is astounding. Currently, in accordance with OPNAVINST 3100.7c, Preparing, Maintaining and Submitting the Ship's Deck Log, electronic deck logs are allowed and this reduces the amount of paperwork a great deal. However, it does increase the complexity of the logging process itself. There must be a computer designated for deck log use; the computer should be near the Officer of the Deck (OOD), and the deck log cannot be compromised or lost due to the single computer's failure. The use of a tablet type device linked to the ships unclassified LAN through a wireless connection would allow the OOD freedom to move throughout the bridge of the ship and make entries with the device, which are instantly backed up and stored, in a more permanent electronic storage with built in redundancies.

This is not the only log taken onboard U.S. Navy vessels. In addition to the ship's deck log, OPNAV INSTRUCTION 3120.32D requires each ship to maintain a magnetic compass record that records "a log of gyro and magnetic compass courses, adjustments and tests," an engineering log that consists of "a complete daily record by watches of important information about the engineering department and the operation of the propulsion plant," this also includes the engineer's bell book that records "a chronological record of orders pertaining to the speed of the propulsion engines or motors." These are only the four logs required by the SORM; they are not every log on board the ship.

Onboard U.S. Navy nuclear powered submarines there are numerous watch standers. The majority of the watch standing personnel, especially in the engine room of the submarine, take log notes on their designated equipment on an hourly basis. This requires the watch stander to write down the required information into a 4 mm by 4 mm box for every required indication. On some of these log sets there can be numerous logs with different meanings. Each log set can be as long as seven pages with 20–30 required entries on each page. These log sets, while underway, are taken every hour on the hour for 24 hours and then a new set is started. The watch standers are trained to record and report indications that are out of specification and in some cases to take immediate actions based on those indications. They are also trained to look for trends in the logged data.

For example, for a bearing that is cooled and lubricated by lube oil the maximum specification may be 120^{o} Fahrenheit (F). If the machinery the bearing is attached to operates at a steady state speed and loading then over time, if there is an increase in temperature, the operator can take action before the temperature reaches or exceeds 120^{o} F. This is because trained operators can recognize a steadily increasing temperature as they log the information every hour and realize that at some point in the future the reading will exceed the specification. This is the simplest case of trend analysis and reaction, but it is not the only case. On the propulsion trains of U.S. Navy vessels, there are multiple oil lubricated bearings between the main engine or gas turbine and the propeller or propulsor. These bearings are not as homogenous as would be expected. A quick look at a given set of logs would show an almost random looking set of numbers as the temperatures of each bearing differs slightly, and all the bearing temperatures increase and decrease over time. This overall increase and decrease in temperature is usually due to changes in the speed and loading of the propulsion system. At low speeds and low loads, the temperatures are going to be lower than at high speeds and higher loads. This raises the question of the viability of trend analysis. Even well-trained experienced operators cannot be expected to see issues with their equipment in this case. To further exacerbate this issue, logs are only taken once an hour. In 60 minutes, there are many factors that can vary; this includes bell changes and mechanical failures that may lead to bearing damage and ultimately a loss or reduction in propulsion.

With an installed wireless network, each individual indicator could send its bearing temperature to a central processing hub. This data could be sent at the millisecond interval, and processed almost instantly for display and analysis. A computer program could be written that analyzes the data for trends and then warns the operator of a potential problem long before actual damage occurs to the bearing. This data could also be stored and then sent to an ashore facility for more analysis that could be used to generate improved maintenance profiles thus further improving the reliability of a given vessels propulsion system.

3. Communications

In 2001 a study was performed for a master's thesis at Naval Postgraduate School by William G. Wilkins Jr. (2001). This study focused on building a software application designed solely to improve communications during damage control evolutions onboard a submarine. This technology included the use of handheld devices and a wireless network. It states:

> Access to information is the key for efficient communications onboard a submarine. We must continue to reevaluate our systems to determine the best solution. Technology has produced COTS based wireless components that give us the ability to access information in a mobile environment. It provides us more flexibility and increases information flow at a low cost. This thesis takes advantage of this technology by developing Java based application, known as SWIPNet. SWIPNet can be used to provide more efficient DC communications and quicker response times. This improved DC model can ultimately make our submarines safer.
>
> SWIPNet is an example of what we can do with a wireless system. It illustrates forward thinking of current task and procedures. This application and others like it are the future of mobile computing. It is imperative to place these tools into the hands of our personnel today to create a powerful dynamic work environment to meet our demands of tomorrow. (Wilkins 2001, 115)

Without wireless technology use onboard, ships' damage control personnel must use an antiquated system of sound-powered phone lines and written messages that are hand carried to a centralized control area. Discussed next is a typical damage control scenario onboard a U.S. Navy vessel.

In a given space onboard a ship there is a fire in an electrical component. A watch stander sees the fire and recognizes it as an issue that he needs to report. This person walks to the nearest sound-powered phone (an internal phone system onboard U.S. Navy vessels that uses electro-mechanical transducers to generate an electric current that activates a speaker at the other side of the connection allowing two or more personnel to communicate without the need for external power) and reports the fire to the appropriate supervisor. The supervisor then uses her sound-powered phone set to inform the OOD, who is in charge of the vessel and on the bridge, of the fire and the location. The fire is announced over the ship-wide amplified announcing system, and all personnel are directed to perform certain tasks in order to prevent further damage to the ship. If the fire grows out of control, then it may become necessary to further enhance the safety posture of the ship by securing various ventilation ducts and water tights hatches and doors, this requires numerous individual reports to the centralized control area stating that designated areas of the ship have been placed in this safer condition known as Condition Zebra. On a surface vessel, the "flying squad" is called away to be the first responders to the fire. They must don their firefighting equipment and enter the space with fire suppressing equipment, which can be a traditional fire hose and nozzle, a CO2 extinguisher, or a PKP extinguisher that extinguishes a fire by interrupting the chemical process. Along with all this equipment, one member of the first response team must maintain communications with the centralized control area. Assuming the first responders cannot extinguish the fire, they are relieved by the ship's crew and exit the area. The ship's crew must then extinguish the fire and maintain accurate communications with the central control area all until the fire is completely out and a reflash watch is set. This is a person with a CO2 fire extinguisher who watches the area where the fire was in order to prevent the fire from restarting. The personnel in charge of the damage control area must maintain a detailed understanding of where the fire is, how big the fire is, what personnel are currently fighting the fire, what personnel are standing by to enter the space, and a myriad of other details that ensure the most efficient and safest extinguishing of the fire. This level of command and control requires the accurate, unburdened flow of information

between multiple sources simultaneously. Below is an example checklist from COMNAVFORINST 3541.1, the Standard Repair Party Manual for Naval Surface Force.

TAB B - REPAIR PARTY LEADER’S (RPL) FIREFIGHTING CHECKLIST

___ Fire/Smoke Reported Compartment_____________________

___ Damage Control Central (DCC)/Command Duty Officer (CDO) Notified

___ Rapid Response Team _____ (Comms) ______ Ckt

___ Check Fire main Pressure (additional fire pumps req?)

___ Damage Control Repair Station Manned/Ready (Comms) Circuit________

___ Zebra Set Time ______

___ Investigators Out (NFTI/Fire Finder issued)

___ Order Fire Boundaries (6 Sides)

___ Order Smoke Boundaries (Smoke curtains, blankets)

___ Order Electrical Isolation (Lighting considerations)

___ Order Mechanical Isolation w/exception of firefighting systems.

(Flammable liquid piping, secure vents, compressed air systems, secure fuel transfers, and heat sources)

___ Space Evacuated/Casualties

___ Space Hazards (Check Chapter 4 Section 2 TAB C)

___ Class of Fire A_______ B___________ C__________ D_________

(Fuel Source)

___ Installed F/F System Activated Time _______

___ FFEs Required?

___ Status of ventilation

___ Status of flammable/explosive spaces near casualty

___ Off Ship Assets Req/Backup Fire Party

Location___________

___ Investigators report in at Least Every 15 Min. – Time_____

___ Fire ____ Smoke ____ Boundaries Set

___ Status of Mechanical____Electrical ____Isolation

Active Desmoking Required?

___ OBA/SCBA Activation Time__________

___ Enter Space - Direct or Indirect Method

___ Forcible Entry Reqd? - PECU/PHARS

___ Status of De-watering Space (Fire Fighting Water (FFW)

Affecting Stability? Space high or Low in the ship?

___ Fire Contained

___ Status of OBA/SCBA men-Coordinate Relief__________ (Location)

___ Fire Out

___ Reflash Watch Set

___ Overhaul

___ Complete De-watering (w/CHENG's Permission)

___ De-smoke (w/CHENG's Permission if Installed Ventilation is to be used;

Ensure Smoke Clears Ship)

___ Affected space gas freed

___ Major Fire-Vital System Restoration-Coordinate with

Each one of these items on this checklist requires at least one communication between the scene of damage and the centralized control center. In some cases, it requires

multiple communications in order to move past a specific point. In the current operational environment, this means each of these communications is passed over the sound-powered phones. This requires one person at the scene in a breathing apparatus of some sort to say loudly the exact piece of information over the sound-powered phone; the receiver at the other end needs to repeat back the information, write it down and then relay that information either vocally or by a written message to the lead officer in the centralized control location. At this point, it may be necessary to update, typically in grease pencil or white board marker, a status board so the information is not lost. This whole process allows for multiple error introductions and is simply inefficient.

In theory, if the ship was equipped with a wireless LAN, then the process becomes much more efficient, accurate and timely. In this scenario, the same on-scene leader could update a hardened tablet of some sort with the pertinent information, and then the information would be immediately displayed on a computer display in the centralized control center as well as the handheld device the on-scene leader is using. This would remove errors in the communications chain, allow personnel to evaluate real-time information and make decisions that can be relayed to the scene immediately. This type of command and control may be the difference between a small fire with minimal damage and a vessel being damaged beyond its ability to self-repair and move forward with its mission.

Other communications that a wireless system would improve include personnel location, updating equipment status, information dissemination, controlling drills more effectively, managing parts inventories, access to digitized technical and repair manuals, and the ability to allow access to a centralized data storage server for a multitude of different tasking (Wilkins 2001). These are not all of the possible communications improvements onboard a ship, but it definitely shows that an installed wireless LAN has many advantages in this field.

4. Data Processing

The information age was ushered in by the generation and subsequent rapid expansion of the publicly accessible World Wide Web. Prior to this development

information was not free and not easily accessible. It was stored in books, which were stored in libraries, either private or public, and a human would be required to physically either go to the location of the information or have the information sent to them by mail. Now that same human can access information databases around the world from their home personal computer. The sheer abundance of available information on the World Wide Web is always a moving number and continues to increase each and every second. Therefore, it is no longer a question of if one can find a specific piece of information; the question becomes how easily one can find that information. The term "Googling" something is now synonymous with searching for some piece of information online. Google was started by two Stanford college students in 1995. By 1998, *PC Magazine* named the company their search engine of choice (Google, Inc 2014). Today, the company is racing Apple Inc. to become the first trillion dollar company by sometime in 2020 (Hallek 2014). How did this company dominate the Internet and grow into a massive corporation and household word? The answer is simple: data processing. They dominated other search engine because they returned relevant results. This means they understood early on the need for processing large amounts of data in order to allow the overwhelming amount of information on the Internet to be sortable and searchable.

As discussed earlier in this paper, the gathering of logged indications wirelessly is a major advantage of incorporating a wireless LAN onboard a naval vessel. This means that data can be gathered at a much faster rate than previously warranted by taking logs manually on paper. Even if the data was sent to a central location only once every second from every wireless enabled indication on a ship, there would be an inundation of data to sort and process. The processing of this data requires the system involved to sort, evaluate trends, provide appropriate operator feedback, and store for future analysis all of the incoming indications all day every day while the systems are in operation. If this is done properly, then there could be major savings in equipment failure prevention, repair dollars, and man-hours expended on repairing damaged equipment. If it is done improperly, then the massive amounts of data could become a burden to the crew and create more problems than it solves.

5. Decrease in Installed Equipment Volume

The Virginia class submarine is only 377 feet long, including the propulsor, 33 feet wide at is widest point in the hull and is designed to carry 117 enlisted personnel with 15 officers onboard. This ship also contains an entire torpedo room with four torpedo tubes, numerous Mk-48 ADCAP torpedoes, 12 vertical launch system (VLS) tubes, a nuclear reactor and accompanying engine room, a kitchen, a dining room for the officers and the enlisted, berthing for almost every member of the crew, and all the various support equipment (Janes 2015). All this is packed inside a relatively small hull. Space onboard the Virginia class submarine is severely limited.

In order to operate a nuclear powered attack submarine, the crew must use the approved and provided operating instructions. These instructions are provided to the crew in the form of large binders approximately 12 inches wide and 15 inches in length with a thickness of up to five inches. A complete volume of operating instructions can span around 15 of these large binders. A quick bit of math reveals that a set of these instructions requires (15 books × 12” × 15” × 5”) = 13, 500 in^3 or 7.81 cubic feet for just one set of these books. The actual space given to all the required manuals onboard is difficult to determine. Another factor that plays into this is that there is sometimes a need to maintain several copies of the same material in different locations for simultaneous use by different personnel. The space required for storing these materials could be alleviated with the use of electronic tablets that are linked to a central data storage device. This would also allow immediate access of manuals and technical documents that are not normally carried onboard the vessel to allow for repairs to be accomplished that would not normally be done due to the lack of available documentation while underway.

Using wireless communications similar to the damage control communications discussed earlier, it is possible to generate, promulgate, and receive accomplishment acknowledgment of orders to watch standers without the need for sound-powered phones. This would mean that the need for a phone booth installation to allow the operators to hear the soundpowered phone communications would be eliminated. This is another possible space saving advantage.

C. THESIS SCOPE

1. Determine the Desired Benefits of Wireless Technology

A systems engineer (SE) in the Department of Defense (DOD) follows a process model (DAU 2015), shown in its most current configuration in Figure 6. Typically, the first step of the process is to determine the stakeholder requirements from a list of a customer wants and needs (Blanchard and Fabrycky 2011). In the case of the DOD, and more specifically the U.S. Navy, those wants and needs typically come from the end users in the various fleets. The wants and needs list must be analyzed in order to find the real problem (Blanchard and Fabrycky 2011). Without an accurate picture of the problem at hand, then the devised or engineered solution may not meet the requirements as stated (Blanchard and Fabrycky 2011).

For a given problem set, a possible solution may be realized in the form of implementing wireless technologies. As discussed earlier, there are a multitude of applications of wireless communication technology that can be implemented as a solution to a given problem.

Before the decision is made to incorporate wireless technology in an enclosed space, it is important to fully understand the benefits of the technology to ensure that the utilization of the given wireless communications system is fully realized. The SE must clearly define the desired functions of the proposed wireless system in order to correctly choose the appropriate equipment to incorporate into the design. This can be accomplished by performing a functional analysis of the problem.

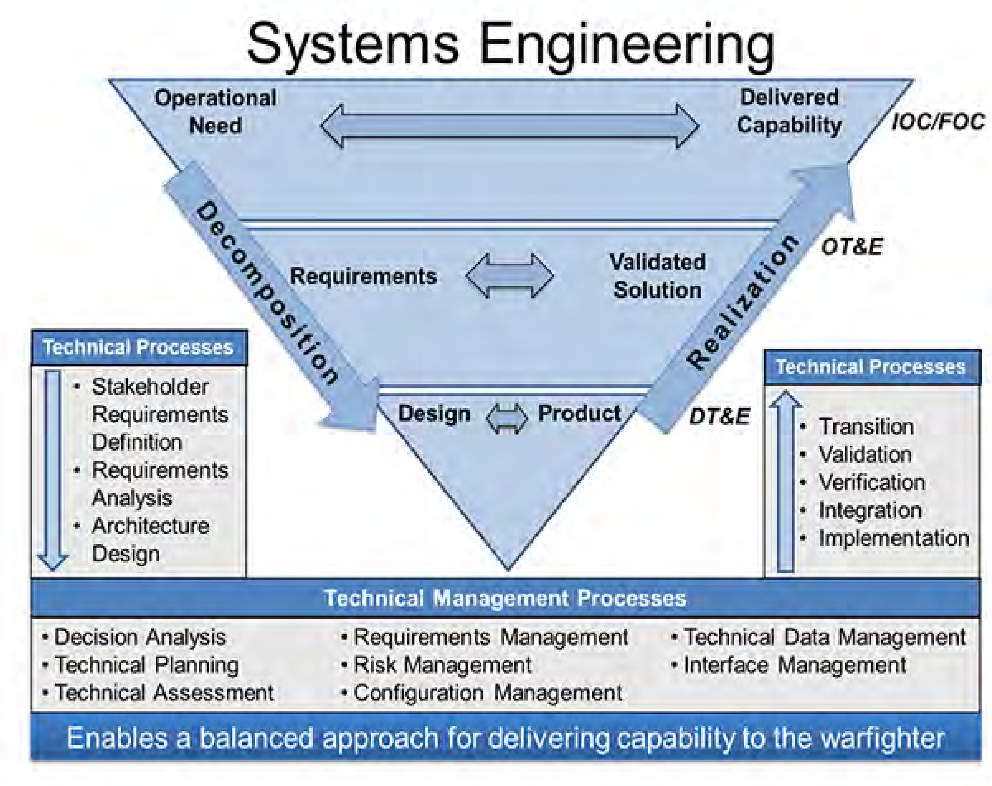

Figure 6. DOD SE Process (from DAU 2015)

The functional analysis of a system ensures that there is an available resource to accomplish the given tasks in the problem statement (Blanchard and Fabrycky 2011). These given tasks can be referred to as functions. A function is specific in nature, and defines what is to be accomplished and not how it is to be accomplished (Blanchard and Fabrycky 2011). Blanchard and Fabrycky state that:

> The *functional analysis* is an iterative process of translating system requirements into detailed design criteria and the subsequent identification of the resources required for system operation and support. It includes breaking requirements at the system level down to the subsystem, and as far down the hierarchal structure as necessary to identify input design criteria and/or constraints for the various elements of the system. (2011, 86).

For a given system the functional analysis can be expressed in the form of a functional flow block diagram (FFBD) as shown in Figure 7. This type of analysis is accomplished by first defining the top level functions of the system then analyzing each

top level function in a subfunction analysis and so forth until all of the required functions are graphically represented and allocated to perform a specific task.

Figure 8 is a generalized FFBD that illustrates the various possible relationships between specific functions at the lowest level of the functional analysis. This type of analysis can be performed a multitude of ways. For this paper, it is not important for the SE assigned to wireless communications analysis to perform the functional analysis, it is important for the SE to extract the various functions from the analysis that may be performed or enhanced with the use of a wireless technology.

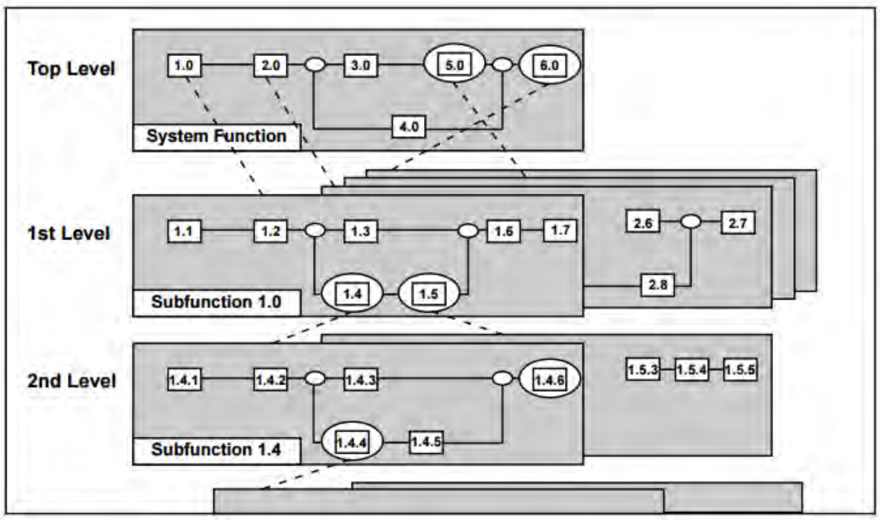

Figure 7. FFBD Level Breakdown (from DAU 2001)

The focus of this thesis is wireless communications within enclosed spaces, and more specifically enclosed spaces onboard naval vessels. Most ship designs will section off portions of the ship based on the function of that space. For example, there will typically be a portion of the ship specifically designed to enclose the combat controls for the sensors and weapons installed on the ship. In this particular space, there will be numerous systems performing different tasks. Each of these systems will be performing different tasks and functions, and each one may benefit from the application of wireless technologies. It is the task of the systems engineering team to determine all the specific

functions in a given space from the various system functional analyses that will or will not be fulfilled entirely or partially with the assistance of a wireless technology.

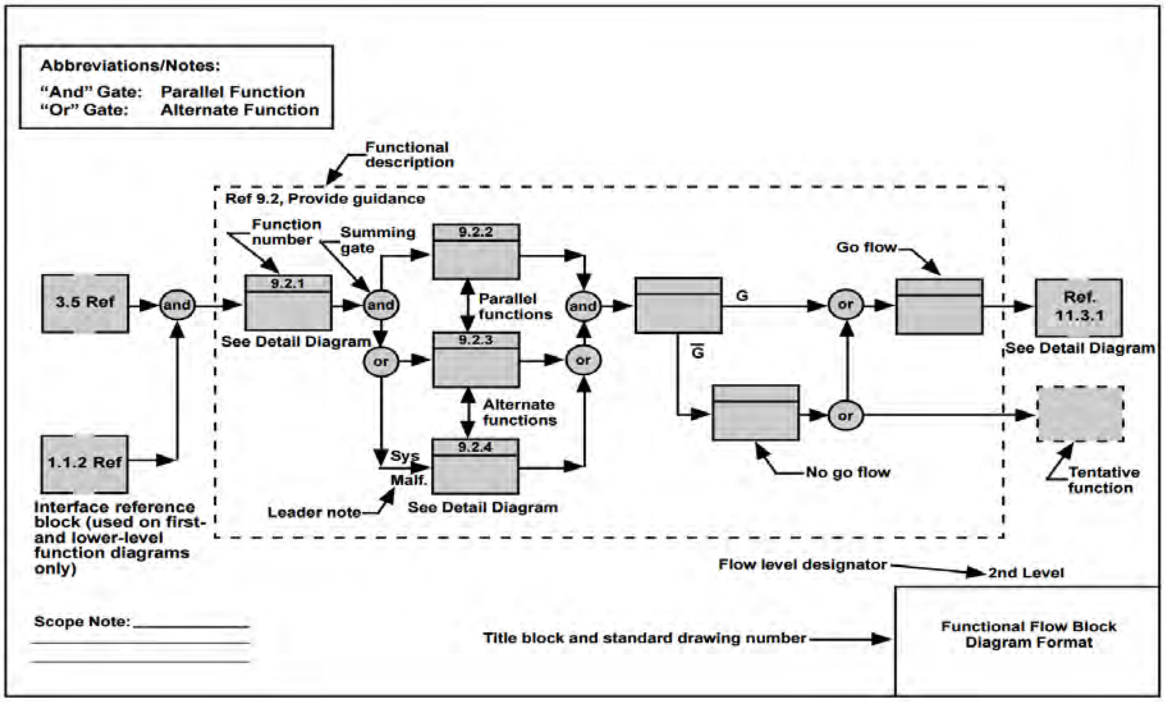

Figure 8. Functional Flow Block Diagram (FFBD) format (from DAU 2001)

Since the bulkheads between spaces onboard U.S. Navy vessels and the walls between spaces in a building tend to either completely block or severely degrade wireless signals, this thesis will consider the effects of wireless communications and their associated EM radiation on a space-by-space basis with a built in consideration for connected spaces.

Once the specific function(s) are identified and a wireless communication device(s) is selected as the possible solution to performing the function(s) it is important for the systems engineering team to evaluate the space as a system of systems and determine the increased risk to the installed electronic equipment.

2. Risks

In most civilian applications EMI is tolerable at some level. For instance, if a hand-held cellular phone is connected to a speaker system using Bluetooth wireless technology and another cell phone is brought into the space, there is a possibility the interference may disturb the signal or cause a disconnection. In this case, the worst possible outcome is that the music stops playing until either the interference is removed or the users determine the cause and repair it.

Even in larger civilian wireless networks, disturbances and failures of data transfer are not critical losses to the users and/or operators of the systems. There may be some time span of system unavailability or system unreliability, but these are easily overcome or adapted to. Contrarily, for military applications even a small loss of data transfer can cause the failure of mission-critical systems. For example, a U.S. Navy Destroyer (DDG) is operating in a missile defense capacity and senses a missile threat that it is then tasked to intercept and destroy, but the assigned interceptor weapon will not engage because the firing signal is being degraded or interrupted by EMI. In this case, there is the possibility for mission failure and with mission failure comes the loss of life and strategic resources; therefore, the system cannot be designed with unacceptable levels of EMI. The failure of a single component in a mission critical system is overcome in the military with designed redundancy and spare parts carried on board; however, relying on these aspects is not acceptable in most cases.

This means that the introduction of EM energy, intentional and unintentional, into any space must be done by design with the benefits and risks fully understood and accounted for.

3. Thesis Scope

a. Example Space

Every system is defined by its boundaries. By what is in the defined boundaries and what is not in the defined boundaries (Blanchard and Fabrycky 2011). In a given enclosed space there may be many individual systems performing their given tasks. These systems have their own boundaries that define them. They may have interfaces

which allow them to interact with other system thereby creating a new, more complex system. Therefore, it is incumbent upon the SE to accurately define the system boundary(s) and system interface(s) in order to fully understand, not only the system operations and benefits, but also to comprehend fully and document the risk of loss due to the designed attributes of a given system.

For the purposes of this paper and the following discussions, the system being discussed is an enclosed space onboard a Navy vessel. For ease of understanding and description this space will be as shown in Figure 9.

This is a completely fictitious space, but is similar in design to those aboard Navy vessels used today. The thick black rectangle is the walls or bulkheads of the space and in this case represent the system boundary for analysis of the EMI inside this enclosed space as long as the door is shut, which is assumed for now. The smaller rectangles inside the space represent the different structures and systems found inside the space. For the purposes of this study, there are six sets of computer cabinets that are required for the proper functioning of the control panel.

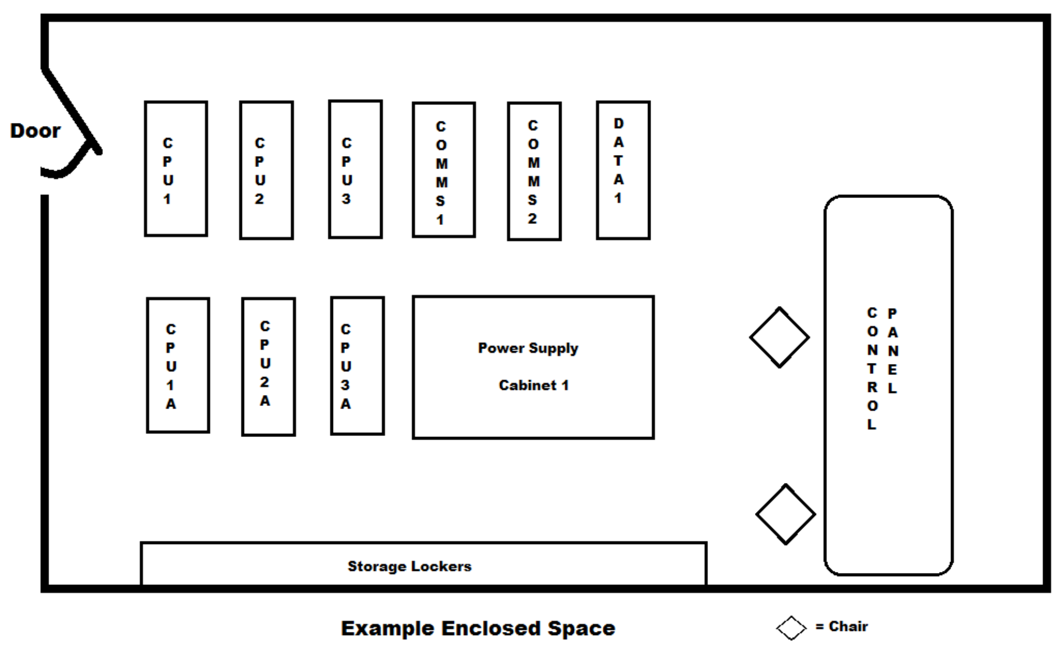

Figure 9. Example Enclosed Space

These computer cabinets are labeled CPU1, CPU2, CPU3, CPU1A, CPU2A, and CPU3A. CPU1, CPU2, and CPU3 are always on and in operation to support the control panel and its functionality. CPU1a, CPU2A, and CPU3A are all normally shutdown and serve as backup components to CPU1, CPU2 and CPU3. The rectangles labeled as COMMS1 and COMMS2 include the interface equipment that allow the components in CPU1-3 to communicate with the control panel (COMMS1), and communicate between the control panel and its designated weapons/sensor system (COMMS2). Power Supply Cabinet (PSC) 1 contains a well shielded step-down transformer and supplies electrical power to every other cabinet in the space including the control panel. The cabinet labeled DATA1 is simply a large set of hard drives where all operations of the control panel are recorded for further evaluation. The rectangle at the bottom of the space labeled Storage Locker represents a simple set of metal lockers for parts storage and personnel use. For the purposes of this study each cabinet, including the control panel and storage locker, reaches from the floor to the ceiling.

The system boundary in this case as previously discussed is the line representing the space bulkheads. This assumption then relegates each system inside the boundary into a component of the larger system. Without the introduction of an EM emitter in the example space, there will be EM radiation levels already present from cableways, and near field effects. This EM radiation can be determined by testing the specified equipment prior to installation and inspecting the EM levels after the equipment is installed. Therefore, the EM radiation levels while operating with the required equipment should be a known quantity and must be accounted for as a whole in the system design analysis when selecting the frequency and power level of an installed intentional emitter.

As discussed earlier, with higher levels of EM radiation in a given space, such as the example space, the installed equipment will experience a greater probability of EMI related deficiencies and accelerated end of life concerns. These effects come at a cost to the system in the form of dollars spent.

b. EM Radiation Emitters

For the purposes of this paper, two categories of EM radiators will be discussed. These two categories of emitters are intentional and unintentional. Intentional EM emitters include any devices that are part of the example space system of systems that are designed to be physically located within the defined enclosed space. The most common examples of this type of emitter are a WLAN router, wireless range extenders, wireless enabled data collection devices, and handheld tablets specifically designed to interact with the installed WLAN.

The following guidelines are quoted directly from MIL-STD-464C, which is the Department of Defense Interface Standard for Electromagnetic Environmental Effects for Systems. It states that:

> For ship and submarine applications, electric fields (peak V/m-rms) below deck from intentional onboard transmitters shall not exceed the following levels:
>
> a. Surface ships.
>
> 1) Metallic: 10 V/m from 10 kHz to 18 GHz.
>
> Intentional transmitters used below deck shall be limited to a maximum output of 100 milliwatt (mW) effective isotropic radiated power (EIRP). The total combined power radiated within a compartment and within the operating frequency band shall be limited to 550 mW total radiated power (TRP). Additionally, no device shall be permanently installed within 1 meter of safety or mission critical electronic equipment.
>
> 2) Non-metallic: 50 V/m from 2 MHz to 1 GHz; Metallic limits apply for all other frequency bands
>
> Intentional transmitters used below deck shall be limited to a maximum output of 100 milliwatt (mW) effective isotropic radiated power (EIRP). The total combined power radiated within a compartment and within the operating frequency band shall be limited to 13.75 W total radiated power (TRP). Additionally, no device shall be permanently installed within 1 meter of safety or mission critical electronic equipment.
>
> b. Submarines.
>
> 5 V/m from 10 kHz to 30 MHz and

> 10 V/m from 30 MHz to 18 GHz.
>
> Intentional transmitters used below deck shall be limited to a maximum output of 25 milliwatt (mW) effective isotropic radiated power (EIRP). The total combined power radiated within a space and within the operating frequency band shall be limited to 250 mW total radiated power (TRP). Additionally, no device shall be permanently installed within 1 meter of safety or mission critical electronic equipment.
>
> Compliance shall be verified by test of electric fields generated below deck with all antennas (topside and below decks) radiating and adherence to the total radiated power limits indicated. (DOD 2010, 10–11)

For the purposes of this paper, it is assumed that all intentional emitters that are designed into the system of systems and/or example space will meet these requirements. It is also assumed that the installed electronic components meet MIL-STD-461F requirements for EMI susceptibility. The intent of the MIL-STD-461F requirements can be found in Appendix A of the manual, but in short, they are intended to prevent degradation to equipment placed in EMEs.

The second type of emitter of concern is the unintentional EM emitter. This is defined as any EM emitter that is in a space without it being there by design. The most common unintentional emitters include cellular phones (personal and employer provided), Wi-Fi enabled personal devices such as tablets and laptop computers, and hand held two-way radios.

These unintentional emitters have various frequency bands, diverse average radiated powers, and a wide array of communication protocols. It is outside the scope of this thesis to attempt to describe and account for every possible unintentional emitter that could enter this system of systems, so for the purposes of this paper the analysis as described below will simply use the general term unintentional emitter for any of these devices.

c. Other Assumptions

It is impractical and mathematically problematic to precisely determine the effects of a dynamic EME on the peak electric field in a given space (Tait 2008). The enclosed spaces on board ships are considered reverberant. A reverberant space experiences

significant reflection of EM radiation from the walls and installed equipment (Tait 2008). Due to this the electric field at any point within the space could be much greater than the emitted field strengths of intentional or unintentional emitters (Tait 2008). Any modification to this space can cause a disturbance in the established electrical fields and shift the peak electrical fields in amplitude and location.

This fact indicates a need to study the long-term risk involved with implementing wireless technology into enclosed spaces onboard Navy vessels. While the implementation of wireless technology must be done within the requirements of MIL-STD-464 and MIL-STD-461F there is still some probability of EMI and component degradation due to the unpredictable nature of the cumulative EM buildup in reverberant manned spaces.

As described above there are multiple methods of EMI to be considered with multiple degradation processes. This again makes it impractical and mathematically problematic to precisely model the aggregate EMI effects to ensure that there is no damage or degradation to installed electronic components over a long period of time.

D. PROBLEM STATEMENT

The introduction of various wireless technologies into enclosed spaces onboard U.S. Navy vessels is becoming more common as the Navy trends towards installing newer technologies in order to maintain parity and reduce manning levels. The DOD has implied various restrictions on surface ships and submarines to limit the electric fields in enclosed spaces thus limiting the EMI and component degradation in these spaces.

The current limitations are intended to ensure that installed component degradation and/or damage is not anticipated. These limitations should also prevent long-term effects that may permanently or sporadically disable the functionality of installed components thereby increasing the lifetime maintenance costs, reducing the reliability, and negatively impacting the availability of the equipment.

If the above statements are true, then there will be no statistically significant decrease in component lifetimes or increase in electronic upsets after the introduction of

intentional and unintentional EM emitters into a given space. The purpose of this thesis is to propose a method to assess the risk of introducing EM emitters into enclosed spaces over the long term without specifically identifying all the possible interactions and peak electric fields within a given space.

II. METHODOLOGY

A. FUNCTIONAL DECOMPOSTION

1. Introduction

In order to fully understand the risks involved with introducing EM emitters into a given space, it is important to fully understand what systems are installed in that space and what functions they perform. Once the functions are fully understood, then the risk of losing some or all of the functionality of an installed component can be evaluated. Furthermore, since the wireless technology being introduced into the space may be performing required functions it is important to understand its functions as well. The functions listed below are examples of functions that occur within the above example space.

2. Installed Components

a. To Power/Energize

The first function discussed will be the function of energizing all the equipment in a given space. The installed electronic components in a given space operate with a constant source of alternating or direct current constantly supplied while the component is in operation. This electrical power must originate from either an onboard generator or battery. From there, it is transmitted through conductive wires into various transformers and or power conditioning units into the space and either into a local power supply cabinet or directly to the electrical component itself.

b. To Communicate

The conveyance of information from one node to another node is the definition of communication for the purposes of this paper. The information must arrive at node “A” in its most complete form and then move to node “B” without a significant loss of quality or quantity. If the information is overly degraded or lost entirely, then the communication is a failure. In modern day electronic components data transfer rates are typically rated in the Mbits/second and Gbits/second range.

c. To Store

This function is defined as the components ability to collect data in various forms and retain that data without a loss of fidelity when the data is retrieved at a later time. With the availability of relatively cheap data storage options it is becoming more commonplace for systems to store large amounts of historical data for analysis at shore facilities. This data may include sensor information used in trend analysis or operational data such as location and speed for reconstruction.

d. To Retrieve

This function is defined as the accessing and transferring of data from a stored location to another location either for processing or display. This function is necessary for a system in order to allow that system to access data and use that data in some form. If the data collected is only stored with no available method to retrieve that data, then the data is rendered useless and storage of data is unnecessary.

e. To Control

Depending on the function of the installed equipment in a given space there may be a need for an action or actions to be accomplished. These actions can either be automatically accomplished based on algorithmic control systems or may require a machine-human interface in order for the action to be initiated. In either scenario, a signal is communicated from one component to a separate component or multiple components and that signal carries with it a set of instructions to accomplish a specific task.

f. To Process

This function is described simply as the transformation of inputs into outputs. The desired output of a given component in a system, or system of systems, is dependent on the processes that are programmed into that component. The above functions directly affect this function as they provide the vast majority of the inputs into a component for processing into functionally relevant outputs.

3. Intentional Emitters

a. To Communicate

The conveyance of information from one node to another node is the definition of communication. The information must arrive at node "A" in its most complete form and then move to node "B" without a significant loss of quality or quantity. If the information is overly degraded or lost entirely, then the communication is a failure.

b. To Translate

The conversion of data from digital signals into EM radiation and then conversion of the EM radiation back into a digital signal. In order for wireless technologies to be of use in a system of systems as described above, the installed intentional emitters must translate data at a minimum rate, and with minimal losses in fidelity.

c. To Boost

This function is defined as the increasing of signal strength above baseline in order to ensure the "to communicate" function is taking place. This function typically comes in the form of antenna gain and increasing the amount of EM radiation the intentional emitter is sending into free space. Due to the dynamic nature of an enclosed space that is occupied by humans it may be necessary at times for the signal from the intentional emitter to be increased or decreased to compensate.

d. To Shape

Signal shaping is accomplished by varying the sinusoidal output signal in such a way as to accomplish a specific demand on the given system. The signal emanating from an EM radiation emitter must meet specific demands (Fischer 2002). Generating signals with the least average power output without sacrificing performance is the most likely goal of signal shaping (Fischer 2002).

4. Unintentional Transmitters

a. To Communicate

The conveyance of information from one node to another node is the definition of communication. The information must arrive at node "A" in its most complete form and then move to node "B" without a significant loss of quality or quantity. If the information is overly degraded or lost entirely, then the communication is a failure.

b. To Interfere

For the purposes of this paper unintentional emitters are defined as any EM emitter that is in a space without it being there by design. Therefore, if an unintentional emitter is in proximity of an intentional emitter and emitting EM radiation there is some probability that that EM radiation will interfere with the intentional emitter and cause a change in the intentional emitter functions "to boost" and "to shape" in some manner.

B. PHYSICAL MAPPING OF FUNCTIONS

In Figure 10 objects have been mapped in accordance with the particular functions that allow them to interact. For any given space, system, or system of systems this must be accomplished in order to ensure that the risk determination is as comprehensive as possible. Figure 10 represents just one system inside the system of systems for the given example space. Each system in the space should be mapped out in the same manner in order to assess the example space and its equipment for vulnerability to electronic upsets that may occur due to an EME in the space. In the case of this type of functional mapping the objective is to determine which objects are the most critical to the system operation. As the number of critical components increase, the loss function discussed later in this paper will have to be adjusted accordingly.

Object 1 in Figure 10 with the subtitle (ps) is a power supply. Powers supplies are sometimes but not always collocated with the electronic components to which they provide electrical power. In the case of this generalized functional mapping and in the example space discussed earlier in this paper, the power supply is located inside the

boundary of the system due to it being in the same space as objects 2, 3, and 4. Its functions are to power Object 2, 3 and 4 with the appropriate voltage and current.

Object 2 with the subtitle (cp) is a control panel. This control panel is the human-machine interface, so it provides information and graphic displays as well as physical control options for the human operators. These controls may include such things as a keyboard, various buttons, switches and knobs that allow the operator to send signals to other objects in the system. The graphic displays may consist of various visual presentation entities such as display screens, lights, gauges, or a combination of the three.

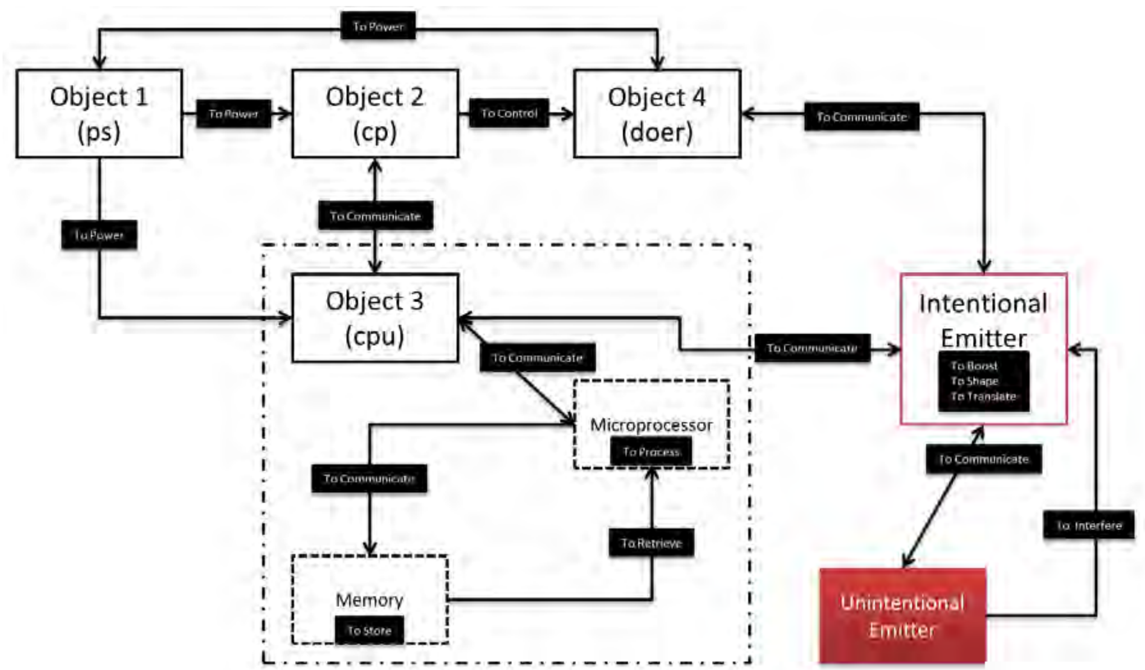

Figure 10. Physical Mapping of Functions

The control panel has three functions associated with it. It is powered by Object 1 (ps), it other objects in the system. The graphic displays may consist of various visual presentation entities such as display screens, lights, gauges, or a combination of the three. communicates with Object 3 (cpu), and it controls Object 4 (doer). As discussed above Object 1 (ps) provides electrical power to Object 2 (cp). In order to provide an appropriate level of information and interaction for the human operators, Object 2 (cp) communicates with Object 3 (cpu) which provides data processing, storage and retrieval.

Once the human operator or Object 3(cpu) determine that action needs to take place, then a control signal is sent to Object 4 (doer).

Object 3 with the subtitle of (cpu) represents a central processing unit. This object is represent in Figure 10 by all the components within the dash-dot rectangle and includes the box labelled Object 3 (cpu), the box labeled microprocessor, and the box labeled memory. The external functional description of Object 3 (cpu) includes receiving the appropriate electrical power from Object 1 (ps) and communicating with Object 2 (cp) and Object 4 (doer). The internal functions (within the dash-dot rectangle) notionally start with some form of data interface in Object 3 (cpu) communicating with the microprocessor. The microprocessor then determines that the data is required to be stored and communicates the data to the memory for long-term storage. In a separate instance of functionality the human operator at Object 2 (cp) initiates a request for data from Object 3 (cpu). In this case Object 2 (cp) communicates with Object 3 (cpu) and the microprocessor processes the request, retrieves the data from memory and communicates the data back to Object 2 (cp) through the data interface. In the final major functional description, Object 4 (doer) communicates with Object 3 (cpu) directly by utilizing the installed intentional emitter, Object 3 (cpu) process the input data and either communicates with Object 2 (cp) or Object 4 (doer) as appropriate.

Object 4 (doer) is the Object that performs the function of the system. For example, if the system in Figure 10 represented a weapons system, then Object 4 (doer) would be the weapon itself. An example is the U.S. Navy’s Mk-45 five-inch deck gun. This gun is operated remotely from the MK-160 Gun Computer System or MK-86 Gun Fire Control during normal operations (U.S. Navy 2013). This gun can be fired remotely from a control panel below deck (U.S. Navy 2013). Object 4 (doer) receives control inputs from Object 2 (cp), and communicates with Object 3 (cpu) through an intentional emitter in this scenario.

The intentional emitter in Figure 10 is represented by a red rectangle and interacts with Object 3 (cpu), Object 4 (doer) and the unintentional emitter. The intentional emitter provides a conduit for communication between Object 3 (cpu) and Object 4 (doer). For the purposes of this paper this decision was made in the initial design process, and is

irreversible. Control functions are not communicated in this manner. Only data is transferred between Object 3(cpu) and Object 4 (doer). The intentional emitter also performs the functions of boosting, and shaping the required signal to limit power output and interference. The intentional emitter also performs the function of translating data to and from EM radiation.

The unintentional emitter in Figure 10 represents any unintentional emitter that enters the enclosed space and is radiating energy in the EM spectrum. For the purposes of this paper, unintentional emitters are allowed to enter the example space and will be used in the risk determination. The unintentional emitter may or may not be allowed to communicate with the intentional emitter, but will in all cases cause some interference with the signal of the intentional emitter.

For the purposes of this paper, the critical functions are evaluated and anything that degrades or interferes with these critical functions is considered an electronic upset. It is not important at this time to demarcate the critical functions specifically in the absence of data relating the EME to upset in these components, but data will be required to properly evaluate the loss associated with an electronic upset.

C. FAILURE MECHANISM

As modern electronics become more advanced their performance increases and our reliance on using them increases (Estep et al. 2012). Furthermore, as the IC becomes more advanced its susceptibility and vulnerability to device failure increases (Estep et al. 2012). EMI is received by wires and traces in printed circuit boards that behave as unintended receiving antennas (Fiori 2001). This in turn creates radio frequency disturbances that affect the operation of the IC (Fiori 2001). EMI is of particular concern when it comes to present day smart power systems that include analog, digital, power and/or radio frequency subsystems on the same IC due to the their proximity (Fiori 2001).

EMI in ICs can cause significant “soft” reversible errors and “hard” irreversible errors. Soft errors include bit flipping, delay/response errors, increased noise and distortion levels, and gain disruption. Hard errors such as gate oxide breakdown, junction filamentation, avalanche breakdown, and metallization/interconnect peel-off can occur as

well (Kim, Iladias, and Granatstein 2004). The mechanisms for these errors are beyond the scope of this paper, but it is important to note that ICs in the presence of an EM field will undergo EMI of some degree and upsets to that IC may occur. Furthermore, the U.S. Navy is currently undergoing efforts to update its electronic componentry in order to avoid obsolescence and limited supply issues. Recent EMI research has shown that with each increase in IC technology the risk of electronic upset also increases (Estep et al. 2012).

Any electronic upset of a given system may or may not be caused by EMI, but research has clearly shown that there is at least the possibility that the rate of electronic upsets will increase in the presence of an EM field.

D. DETERMINING CRITICAL MEASURE OF EFFECTIVENESS

In order to understand the risk to the installed electronic components from intentional and unintentional emitters it is necessary to accurately discover a measure of effectiveness (MOE) that is well-framed and contains both well-defined boundaries and an integrative framework that identifies the domains for assessment (Langford 2014).

The first step in determining the MOE is building the integrative framework.

The integrative framework shown in Figure 11 illustrates, with the use of arrows, the order of the interactions between the objective frame and the subjective frame. There are nine "cardinal points" within the integrative framework; each of these is a result of the intersecting objective frame and subjective frame items and are the domains of the measures of effectiveness (Langford 2014). Figure 12 delineates the domains for the measure of effectiveness.

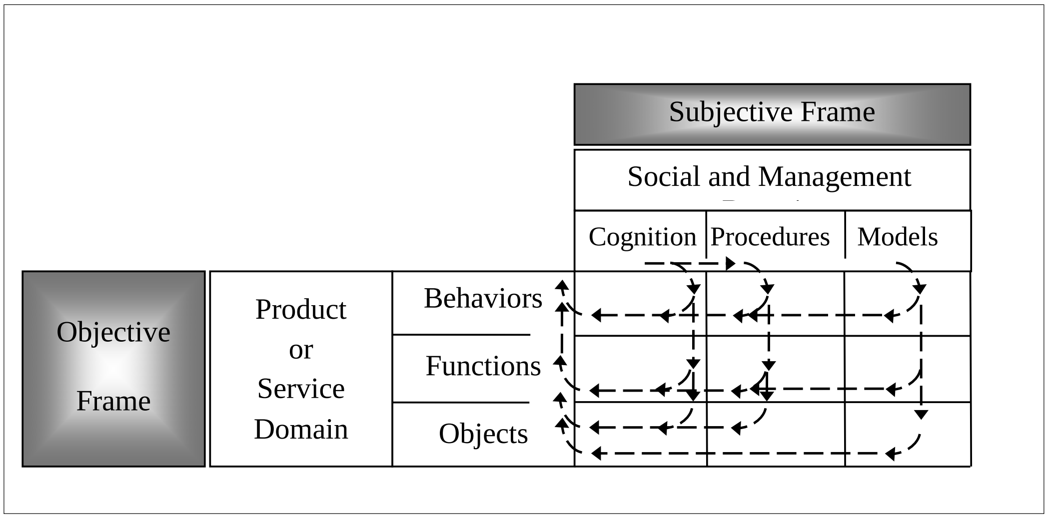

Figure 11. Integrative Framework (after Langford 2012)

			Integration method		
			Processes		
			Abstractions (and reasoning)	Mechanisms, procedures, activities	Models, representations
OBJECTS	Product*Service	User behaviors (associated with or due to product*service)	Conceptualization pertinent to user behaviors due to product*service	Process and mechanisms describing user behaviors due to product*service	Models or representations of the user behaviors
		Functions (associated with or because of objects that comprise product*service)	Conceptualization delineating uses provided by product*service	Process and mechanisms achieving complete portroyal of product*service functions	Models or representations showing all functions
		Physical entities (associated with or because of objects that comprise product*service)	Identifying and interpreting the product*service physical artifacts, and ascribing meaning	Process and mechanisms resulting in the development of all physical elements	Models or representations of all physical elements

Figure 12. Integrative Framework and Descriptions (from Langford 2014)

According to Langford (2014):

> The integrative framework embodies six actions:
>
> A set of basic set of assumptions that show relevance and utility in multiple disciplines, but are not unique to any particular;
>
> A unifying perspective by defining terms to encompass the meanings that are generally in use in systems integration, but not necessarily the nuances that may have evolved due to local norms or conventions;
>
> A wholeness of character through a common structure and set of processes, i.e., integration as is commonly thought to be building a whole from its parts;
>
> The essence, nature, and purpose of interaction leading to systems integration;
>
> A structure that is restrained from being developed into or providing specific strategies for practice, but instead encourages the development of heuristics based on principles derived from theory (rather than from best industry practice); and
>
> A warning that best practices should be inspired by principles and brought under configuration management and vetted by their environment, their context, their broad applicability, their congruency, and their outcome(s). (5–6)

To paraphrase Langford, there is no measure of effectiveness unless there is something to measure in units of some sort and then evaluate or interpret the meaning of the measurement in the context of the system or system of systems Without the full analysis and understanding of the nature of effectiveness the MOE is less meaningful than it should be and may simply be unnecessary or misleading altogether. All MOEs should be focused on the fitness for purpose and not about simply defining generalized outcomes. Whether or not an object functions in a way that fulfills its designed purpose should be the impending user's primary concern (Langford 2014).

For instance, if the object of concern is a ground vehicle and the only MOE for that ground vehicle is only top-speed of 176 +/- 5 mph then the user will only get a vehicle with a specific top speed. If the user wants the ground vehicle to transport personnel 200 miles between refueling at an average speed of 50 mph, then the top-speed

MOE is meaningless as there could be a one gallon fuel tank (just enough to get to the top speed before running out of fuel) then the purpose of the ground vehicle does not match the user's expectations.

Figure 13 depicts the interactions between the objects in a system and the processes in a system in a generalized sense. Even though this framework was developed for use in the design process, for the purposes of this paper it is being used to determine the most appropriate MOE to determine the risk posed to installed electronic components from intentional and unintentional emitters. The focus of the framework is on the boundaries between the objects and the processes (G. Langford 2014). These boundaries, by design, are functional, physical and behavioral by design (Langford 2014). For example, MOE-a is quantified in terms of the degree that developers follow the designated project plan.

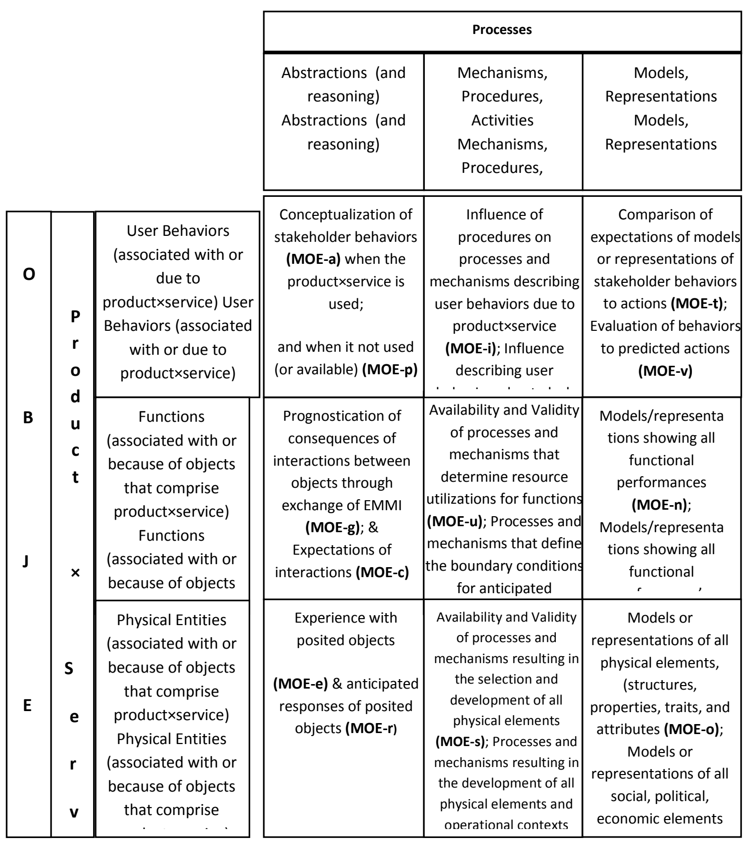

Figure 13. Nine Cardinal Points for Measuring Effectiveness (from Langford 2012)

(MOE-a) Conceptualization of stakeholder behaviors when the product × service is used;

(MOE-p) Conceptualization of stakeholder behaviors when the product*service is not used (or available);

(MOE-g) Prognostication of consequences of interactions between objects through exchange of EMMI;

(MOE-c) Expectations of interactions;

(MOE-e) Experience with posited objects;

(MOE-r) anticipated responses of posited objects;

(MOE-i) Influence of procedures on processes and mechanisms describing user behaviors due to product*service;

(MOE-f) Influence describing user behaviors due to lack of product*service;

(MOE-u) Availability and Validity of processes and mechanisms that determine resource utilizations for functions;

(MOE-b) Processes and mechanisms that define the boundary conditions for anticipated operations of all functions;

(MOE-s) Availability and Validity of processes and mechanisms resulting in the selection and development of all physical elements;

(MOE-x) Availability and Validity of processes and mechanisms resulting in the development of all physical elements and operational contexts;

(MOE-t) Comparison of expectations of models or representations of stakeholder behaviors to actions;

(MOE-v) Evaluation of behaviors to predicted actions;

(MOE-n) Models/representations showing all functional performances;

(MOE-q) Models/representations showing all functional performance’s quality;

(MOE-o) Models or representations of all physical elements, (structures, properties, traits, and attributes;

(MOE-j) Models or representations of all social, political, economic elements;

In Figure 14 the integrative framework method was applied to the process of determining if there will be an electronic upset within the aforementioned system in our example space. Due to the nature of the integrative framework method not all of the MOE's listed were necessary to determine that the MOEs to focus on. These are the upset rate of installed components (MOE-g) and the documentation of the installed equipment nominal quality to include the variance from that quality (MOE-g).

The representative physical model of the installed components, intentional emitter and unintentional emitter is as discussed in section II.B.1.

	Process: Determine if there will be an electronic upset (hard or soft)		
	Cognition	**Procedures**	**Models**
Behavior	To Investigate Error MOE-a	Standard Operating Procedures MOE-f	Follow the procedures to achieve outcome of (what is wrong) MOE-t
Function	Number of Upsets of Installed Components MOE-g	To Achieve the Required System Availability MOE-u Determine Variance form Nominal Quality MOE-b	Build a Functional Model of Probability of Electronic Upset MOE-n
Object	Corrective Maintenance or Object Reboot for Installed Components, Intentional Emitter and Unintentional Emitter MOE-e Installed Component, Intentional emitter, and Unintentional Emitter recovers from Upset MOE-r	Correctly Perform Troubleshooting Procedures on Object MOE-s	Representative Physical Model of the Installed Components, the Intentional Emitter and the Unintentional Emitter MOE-o

Figure 14. Integrative for Determining Risk MOE

E. RISK

1. Definition of Risk

Risk is made up of two main components: the probability that something is going to happen and the consequences of that something happening (Aven 2012). The probability of an event occurring is simply a measure of how many times in a given measure that something happens. For instance, if a human wants to understand the probabilities associated with how they are going to die, they can simply determine this by dividing the number of deaths from a given cause in a given population that they belong to by the number of human deaths in that population. This is an oversimplification of the probability of certain deaths but can give a rough estimate as seen in Figure 15 as expressed in odds. Therefore, a human has a 1 in 7 chance of dying from heart disease or cancer and a 1 in 8015 chance of dying in an air or space related accident (National Safety Concil 2015).

The decision to do a certain task can be aided by looking at the probability of that task killing the human. Certain tasks or activities will increase the probability that the human will die and others will reduce the chance. For instance, there is a 1:112 chance every time a human operates a vehicle, that they will perish (National Safety Concil 2015), but every time that same human flies in a plane, the probability of their demise is much less since only one out of eight thousand or so humans expire in that manner.

Death is a severe consequence, and not all actions will result in death; it is simply one outcome of a set of choices available to the human. Assuming that the human does have an automobile accident while driving, then the consequences of that accident may be very minor such as slight damage to the vehicle and no human damage, or it may be a total loss of the vehicle and major human damage. So the consequences of an event occurring are the second half of the risk equation. So the overall risk from the human’s perspective is dependent on both the probability of an event occurring and the severity of the consequences of that event.

Cause of Death	Odds of Dying
Heart Disease and Cancer	1:7
Chronic Lower Respiratory Disease	1:28
Intentional Self-harm	1:100
Unintentional Poisoning By and Exposure to Noxious Substances	1:109
Motor Vehicle Crash	1:112
Fall	1:144
Assault by Firearm	1:358
Pedestrian Incident	1:704
Motorcycle Rider Incident	1:911
Unintentional Drowning and Submersion	1:1,113
Exposure to Fire, Flames or Smoke	1:1,442
Choking from Inhalation and Ingestion of Food	1:3,375
Pedacyclist Incident	1:4,535
Firearms Discharge	1:6,699
Exposure to Excessive Natural Heat	1:6,745
Cataclysmic Storm	1:6,780
Air and Space Transport Incidents	1:8,015
Exposure to Electric Current, Radiation, Temperature and Pressure	1:12,220
Contact with Sharp Objects	1:37,351
Contact with Hornets, Wasps and Bees	1:55,764
Contact with Heat and Hot Substances	1:59,093
Legal Execution	1:127,717
Being Bitten or Struck by a Dog	1:116,448
Lightning Strike	1:164,968

Figure 15. Probability of Specific Causes of Death in United States (from National Safety Concil 2015)

This paper will first look at loss function as a measure of the consequences of EMI and then a discussion on the probability of electronic upset followed by the determination of risk as a function of the two.

2. Loss Function

In the manufacturing process there are multiple specifications that determine the quality of a product. In the past most industries used a binary process for quality control purposes. This meant that if a product specification was 1.0 inches to 1.5 inches, then any time the product was delivered and that specification was measured if the distance was less than 1.0 inches or greater than 1.5 inches the product was rejected; contrariwise, if the measurements of that component were within the specified requirements then the product passed inspection (Roy 1990). Genichi Taguchi introduced the concept of a loss function for the design and building of a particular system. Taguchi defined the loss function as "a quantity proportional to the deviation from the target quality characteristic (Roy 1990)." This means that if given a singular target value for a specification on an item being designed and that item is built with the specification exactly at that specific value then the loss is minimized or zero (Roy 1990). As a mathematical function this can be represented by the loss function f(x) (Yang 2007):

Equation 1. $f(x) = K \times (x - x_o)^2$

where:

x = the quality characteristics, such as a dimension or performance

x_o = The target value for the quality characteristic

K = A constant which is dependent upon the cost structure

A graphical representation of this function is seen below in Figure 16. It is important to note the equation is a second order equation, that the magnitude of the loss increases quickly as deviation occurs and that the function is continuous in nature (Roy 1990).

In Figure 17, the same loss function is shown with a graphical representation of the classic quality control methodology incorporated to highlight the difference in the two methodologies. In the classic function any product with the quality characteristic measured at less than -10 or greater than 10 were rejected, therefore the manufacturing

goal was simply to remain in this zone in order to produce products. The Taguchi method is focused on the process attempting to meet the target goal in order to minimize loss. This type of system design requires forethought and consistent improvements to minimize loss and maximize quality.

This type of loss function is called nominal-the-best (NTB) by Taguchi (Roy 1990), but it is not the only loss function. The other two loss functions used in quality management are the smaller-the-better (STB) and larger-the-better (LTB) functions.

The STB function is used to describe a quality characteristic where zero is the target value and the loss increases as the characteristic increases. From Equation 1 our x_o variable is now equal to zero and we get the following equation (Yang 2007):

Equation 2. $f(x) = K \times x^2$

where:

x = The quality characteristics, such as a dimension or performance
K = A constant which is dependent upon the cost structure

An example of this is shown in Figure 18 below.

The third type of loss function is the LTB loss function. In this case as the quality characteristic increases then the quality of the product also increases. Since this is simply an inverse of Equation 2 we can write this equation as (Yang 2007):

Equation 3 $f(x) = K \times (1/x^2)$

where:

x = The quality characteristics, such as a dimension or performance

K = A constant which is dependent upon the cost structure

These generalized loss functions perform very well when determining the overall performance of creating objects in a factory but they can be modified to elucidate numerous processes that involve a trade-off between loss and performance (Langford 2015). An example of this type of loss function can be shown in Figure 19.

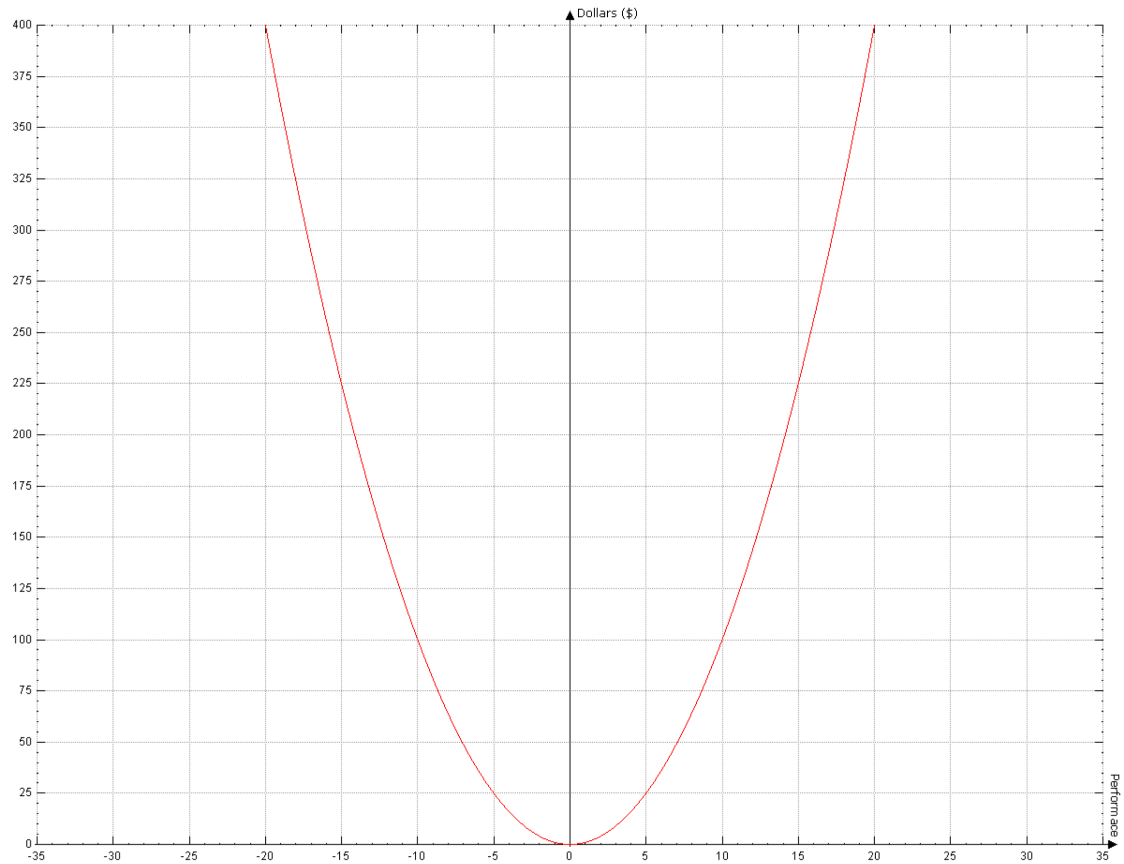

Figure 16. General Taguchi Loss Function

The installed components in an enclosed space on a U.S. Navy vessel must meet minimum standards for electromagnetic compatibility (EMC). This comes at a cost to the component builder and is passed down to the U.S. Navy. It is possible to build and install components that are nearly impervious to EMI and therefore all but eliminate any electronic upsets caused by it. This increased resistance to upset comes at a price. Increased shielding and component design at the IC level are both expensive when considering the number of installed components per ship and the number of ships where the components will be installed. Therefore, the SE must evaluate the trade space to determine where the minimum cost will be incurred for the required EMI resistance.

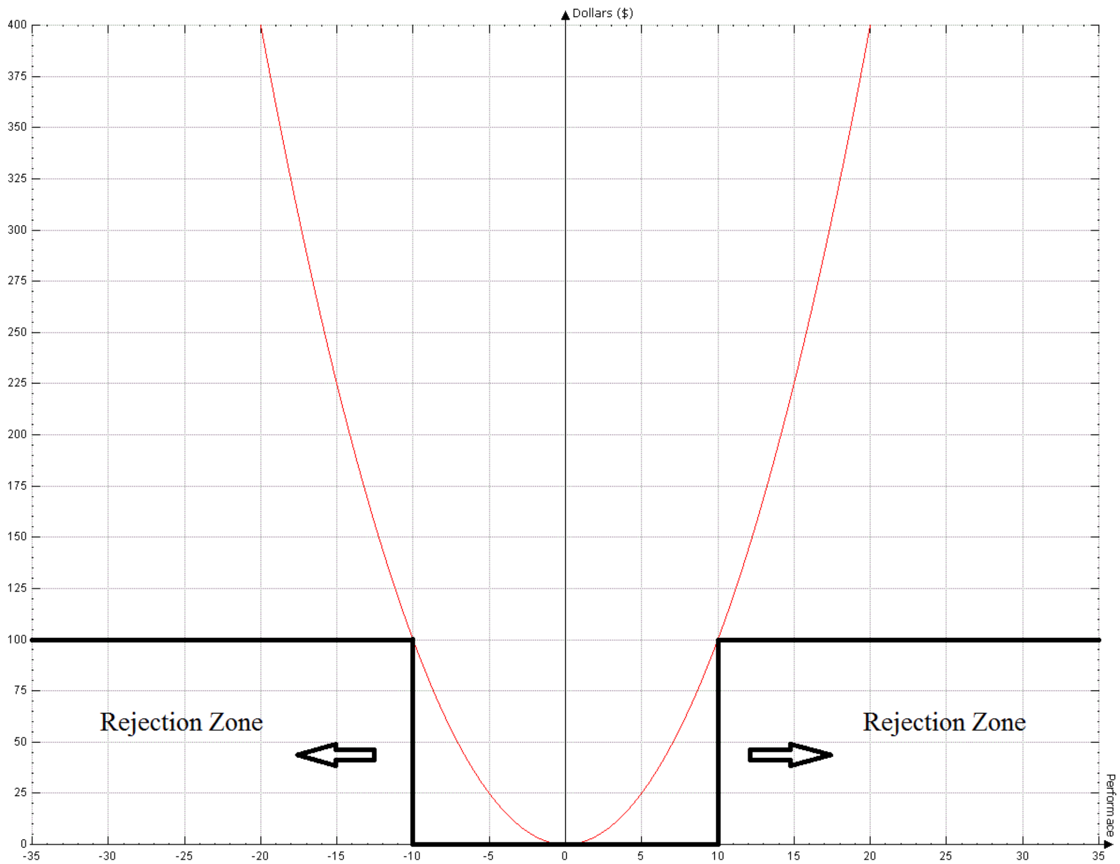

Figure 17. Loss Function with Rejection Zone Overlay

This is where the first loss function comes into play. In this case the LTB loss function is applicable as seen in Figure 20 below. To simplify the visual representaiton the LTB function y = 1/x. On the x-axis is the number of upsets in the installed components. On the y-axis is the loss expressed in thousands of dollars due to designing and building the equipment to resist EMI. This graph is for an example and does not reflect an actual sytem or system currently in design.

For the benefit of explanation it is assumed that Figure 20 represents a real system as designed and has been designed to prevent EMI at some given level expressed as a maximum allowed number of upsets. As the minimum EMI rating for an installed component increases the rate of EMI related upset decreases in a given standing EME. As shown above today's ICs are susceptible to smaller EM radiation fields and therefore

careful consideration must be made when designing and installing components in a space with intentional and/or unintentional emitters.

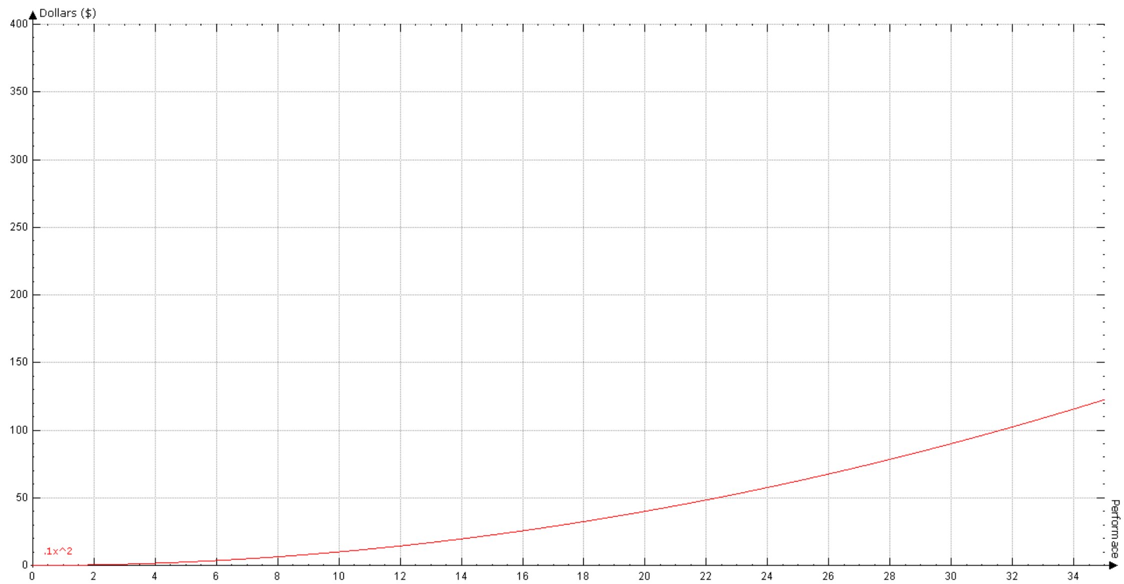

Figure 18. General STB Loss Function

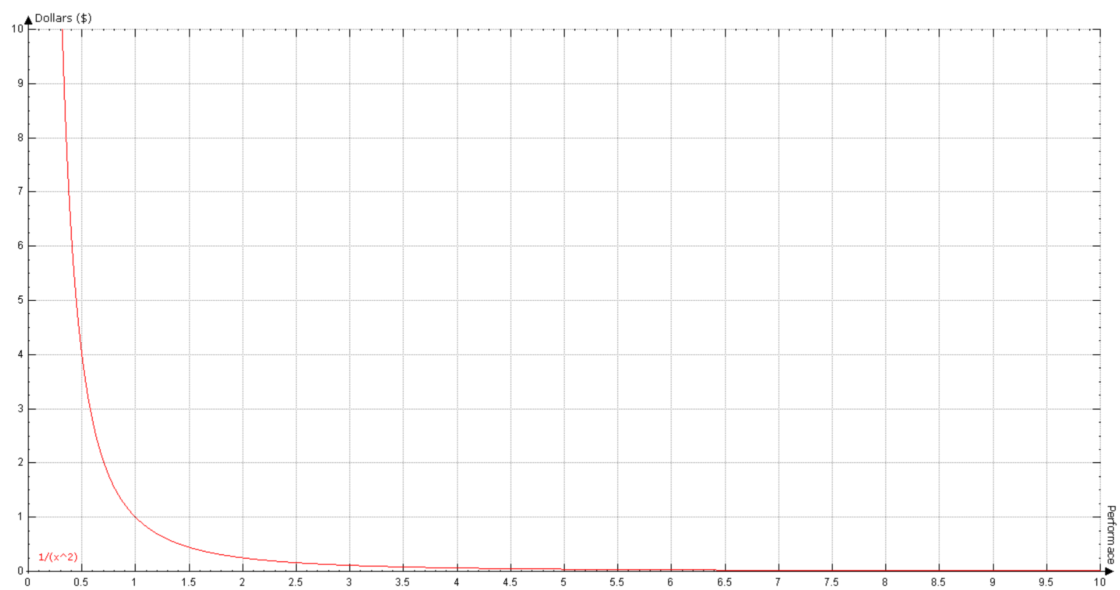

Figure 19. General LTB Loss Function

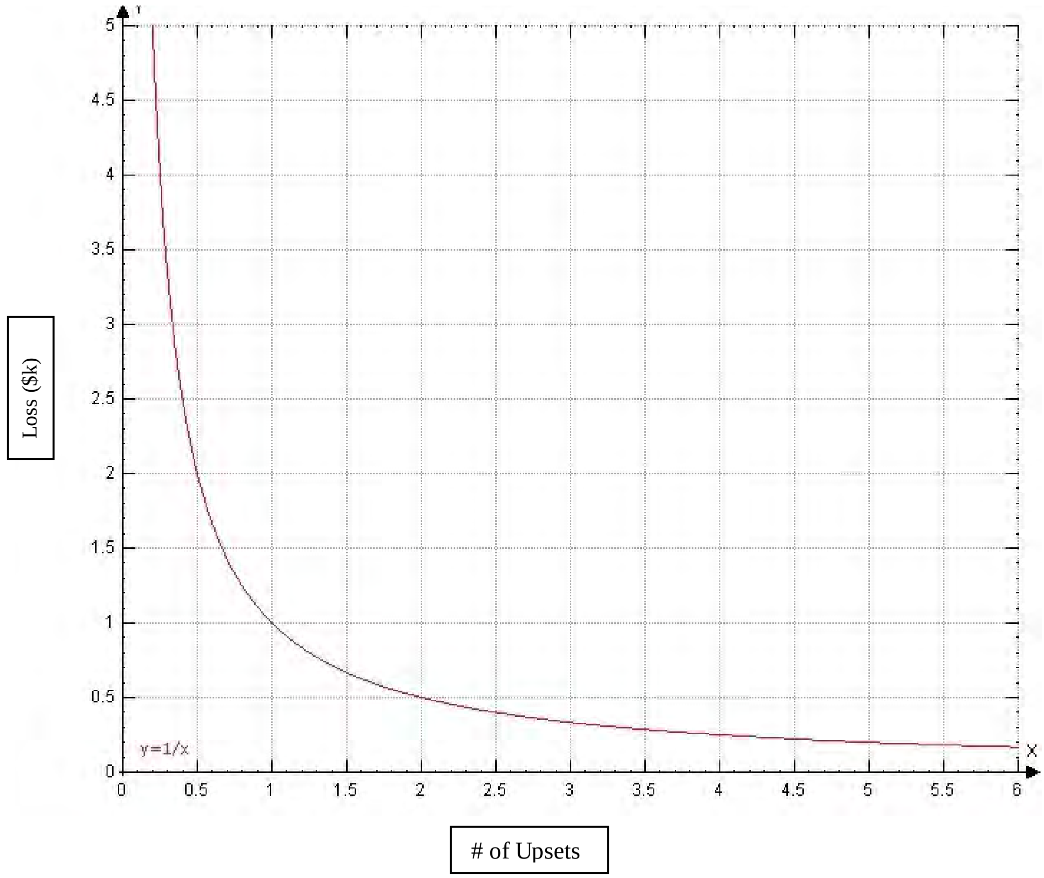

Figure 20. LTB Loss Function (Installed Components)

The second part of developing an accurate loss function for this risk determination is the loss associated with actually placing the intentional emitter in the reverberant enclosed space. This loss function is shown in Figure 21. Another assumption is that with no electric field due to an emitter present, the number of EMI related upsets will be zero.

The curve as shown in Figure 21 depicts a linear relationship between the numbers of upsets seen in the objects with critical functions in the functional analysis with a loss in the form of dollars. This relationship is due to the fact that as sensitive electronic equipment undergoes increased numbers of upsets then that equipment is, generally speaking, more likely to fail, partially or in full, and then subsequently require maintenance which is cost in the form of man-hours or replacement which incurs cost in the purchasing of new equipment. This relationship is most likely not linear in nature but is simplified as such for visual representation and understanding.

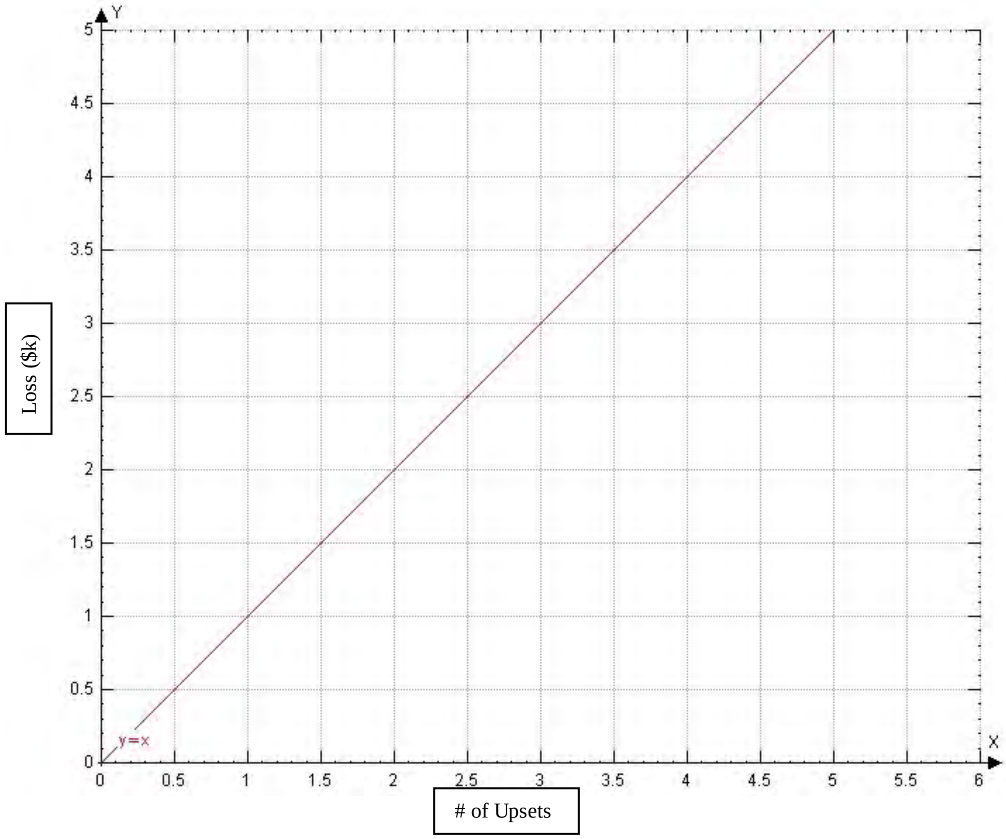

Figure 21. STB Loss Function (Emitter EM field)

Adding these two curves as shown in Figure 22, graphically and numerically reflects the interaction between the installed component resistance and the number of upsets in the installed components in the enclosed space. The resulting equation then becomes $y = x+(1/x)$.

It is this curve that represents the consequences of our risk determination.

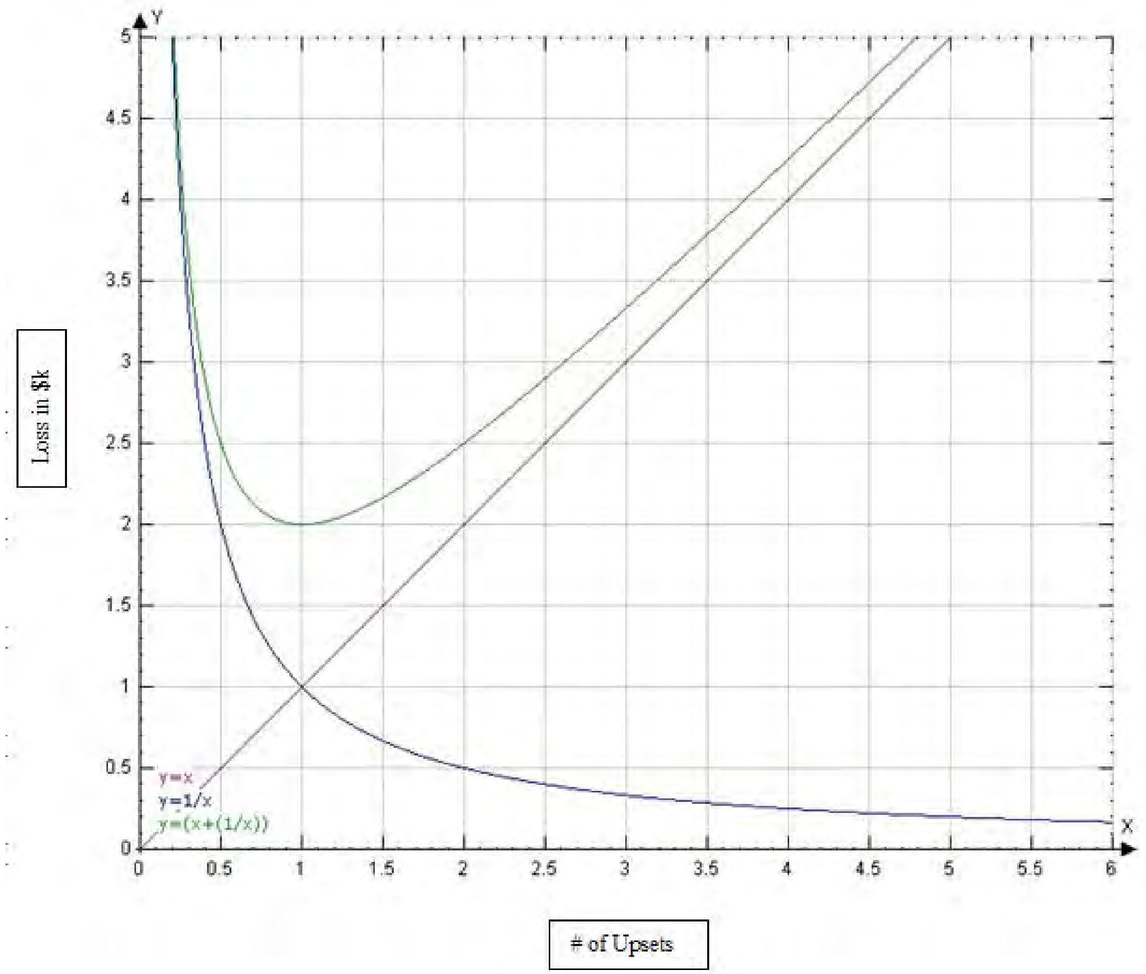

Figure 22. Overall Loss Function

In this case the minimum loss incurred is 2,000 dollars, this is due to the equipment experiencing one upset (at a cost of 1,000 dollars), and the cost of hardening the equipment to a level where the introduction of an electrical field at or below a threshold level will induce one upset in the installed equipment. The maximum loss incurred in the system by design is 2,500 dollars which accounts for two upsets to the installed equipment and the hardening of the equipment.

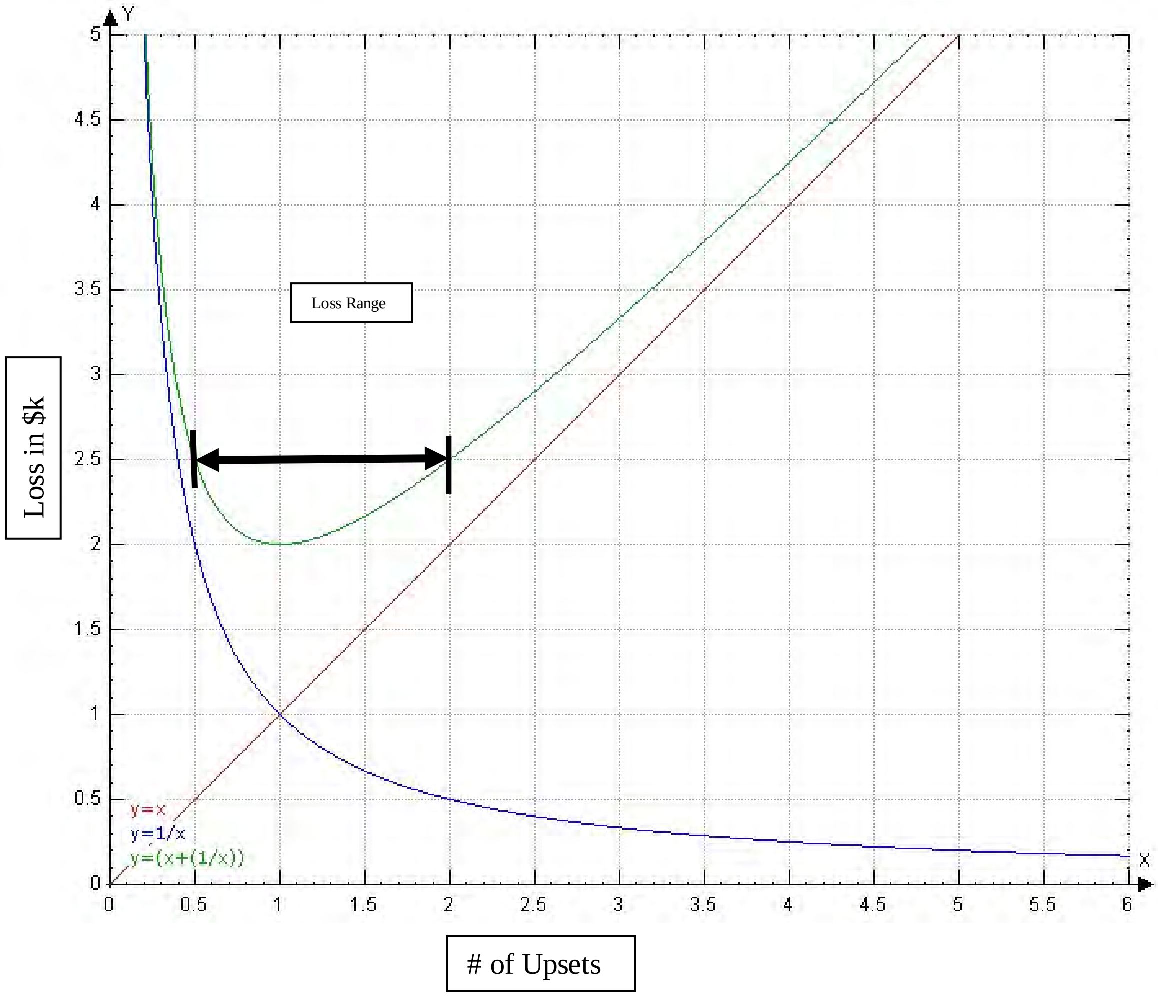

Figure 23. Loss Curve with Emitter Specifications

It is important to note that these curves are notional in nature and require further development to acquire the appropriate shape necessary to create an accurate loss curve. These curves are also only valid within certain ranges which will also be determined through complete investigation of the specific interactions in a given space of concern.

This overall loss is directly affected by the electrical field as seen by the installed components which is not fixed in nature. One consideration in this process is the power spectrum of the intentional emitter. In a static environment with a transceiver on one side of a given space and a transceiver on the other side, the power output of the intentional emitters is maintained at a steady level in order to maintain the required communications. However, when one or more unintentional transmitters enter the same space and transmit

simultaneously over the same frequency band, the data rates are negatively affected by the interference (Tan 2011). Power control is used to improve the spectral utilization and the systems overall performance, these techniques are known as Dynamic Spectrum Management (Tan 2011).

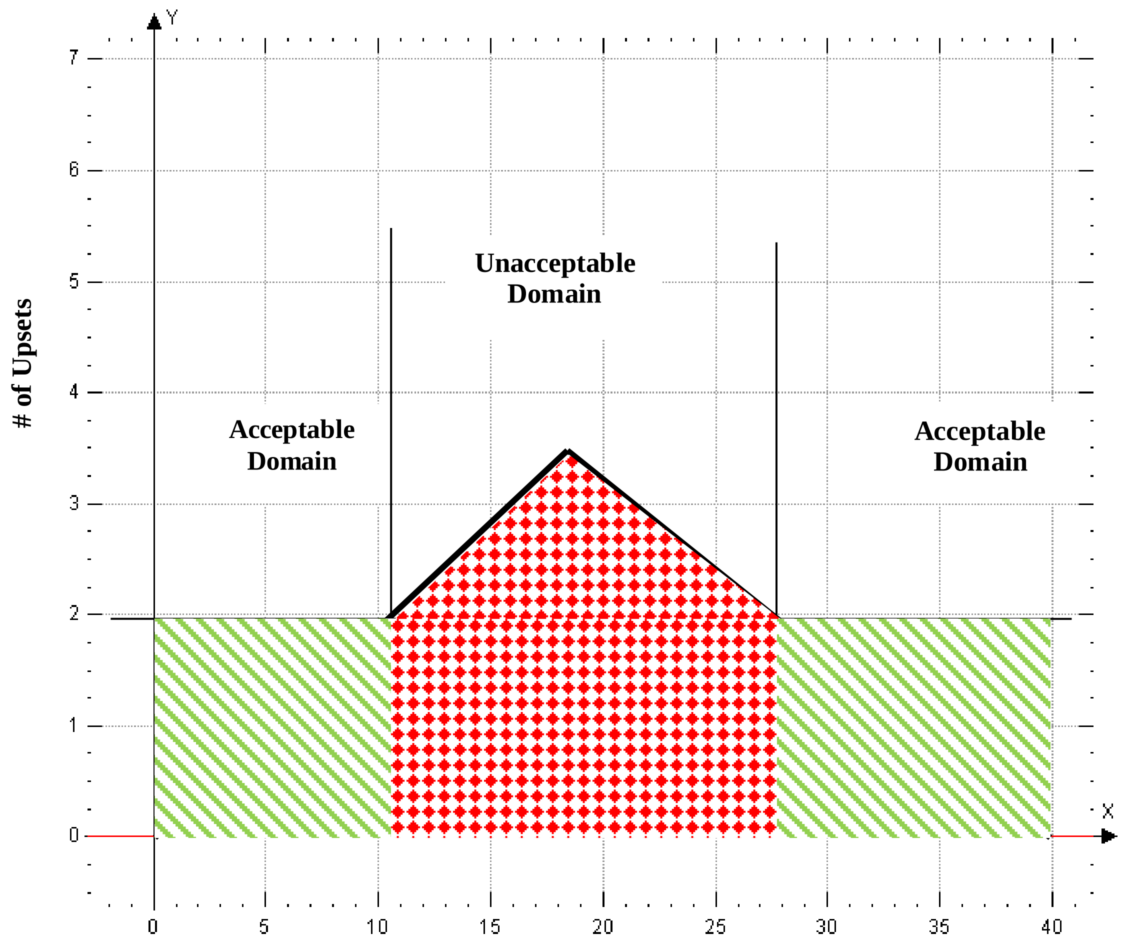

Figure 24. Electrical Fields in Enclosed Spaces Vs. Upsets

The introduction of one or more unintentional emitters in the same space will also increase the overall average electric field in a space, but it too will vary widely based on certain variables such as average power output of the device, location of the device, frequency of the device, and the device(S) Dynamic Spectrum Management (DSM)

protocols. Whenever there is a change to the EME in the given space the intentional and unintentional emitters will compensate by increasing output power. The increased output power will follow an algorithm that controls the duration of the radiated power levels. It is assumed here that (in Figure 24 this is approximately 18 V/m) the more powerful EM radiation events will be of decreasing duration and, therefore, less likely to increase the number of upsets in installed equipment.

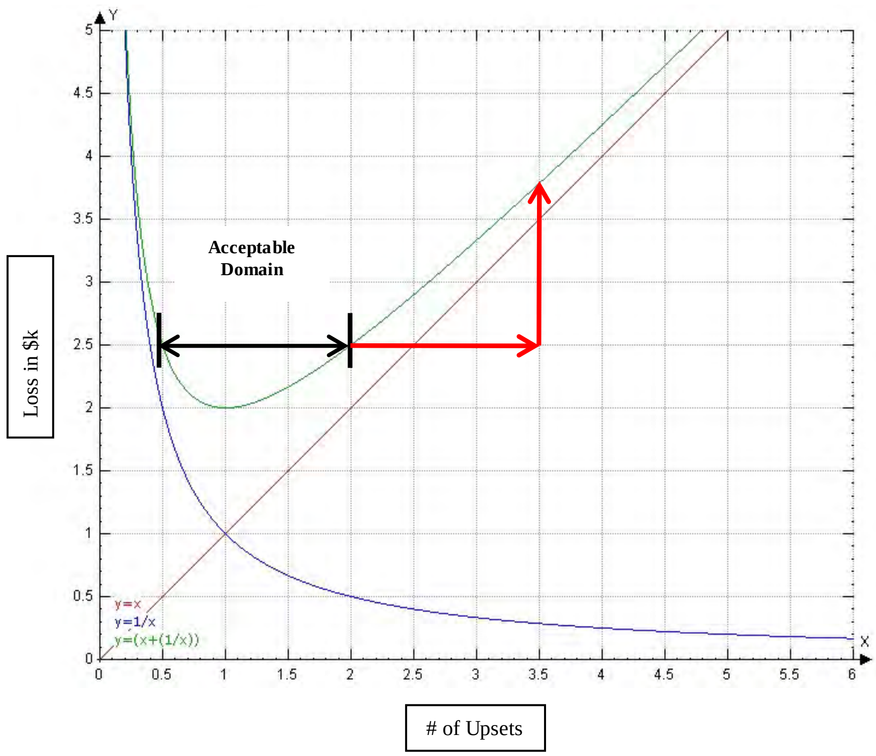

Figure 25. Loss Curve with Worst Case EME

In Figure 25 it is assumed that the worst case EME is occurring in the given space and from Figure 24 we can see that at approximately 18 v/m combined power output from all the emitters in the given space the number of upsets is expected raise to 3.5 with an incurred total loss of 3, 750 dollars. This loss is unacceptable and the need to redesign the parameters of the given space is necessary to prevent the unacceptable loss. The exact measures needed may include increased shielding or procedures that severely inhibit the use of unintentional emitters in a given space. These measures will be discussed in

further detail later in this paper. Note that here the electric field (average and peak) positively correlates to the number of upsets dependent on the design of the installed components and emitters.

Now that the consequences part of the risk equation is laid out in the form of a loss function the second half of the risk function, likelihood, will be described.

3. Likelihood

The enclosed spaces onboard U.S. Naval vessels can be considered EM reverberation chambers due to their EM reflective properties (Vogt-Ardatjew and Leferink 2013). The EM radiation in a given space is reflected and not absorbed when it comes in contact with steel bulkheads and metal equipment enclosures. It has been shown that in some cases a reverberation chamber can create very high field strength with a moderate input power (Leferink 2008). When attempting to determine the average and peak electric fields in a complex space such as the provided example space above the complexity is too high for a deterministic approach (Vogt-Ardatjew, van de Beek, and Leferink 2014). In order to attempt to predict EM field strength at a given time and location within a given space the approach is either to use a simple model with too few assumptions and a few reflections, which is inaccurate to say the least, or use a probabilistic approach (Vogt-Ardatjew and Leferink 2013). Theoretical models assume the usability of the Central Limit Theorem (Vogt-Ardatjew, van de Beek, and Leferink 2014) for this type of analysis since it shows that any sum of many samples will always result in a normal distribution (Vogt-Ardatjew and Leferink 2013). Thus, the EM field is, assuming independent, uncorrelated, normally distributed random variables, distributed according to the Rayleigh distribution as shown in Figure 26 (Vogt-Ardatjew and Leferink 2013).

The electric field strength in a given space can be approximated by a Rayleigh distribution; therefore, based on the previous assumptions the number of upsets in a given system will follow the same type of distribution, and as such will be assumed for the purposes of this paper.

Figure 26 is just one example of one steady state scenario with a given enclosed space. Its parameters and shape will vary based on the present electric fields within a given space.

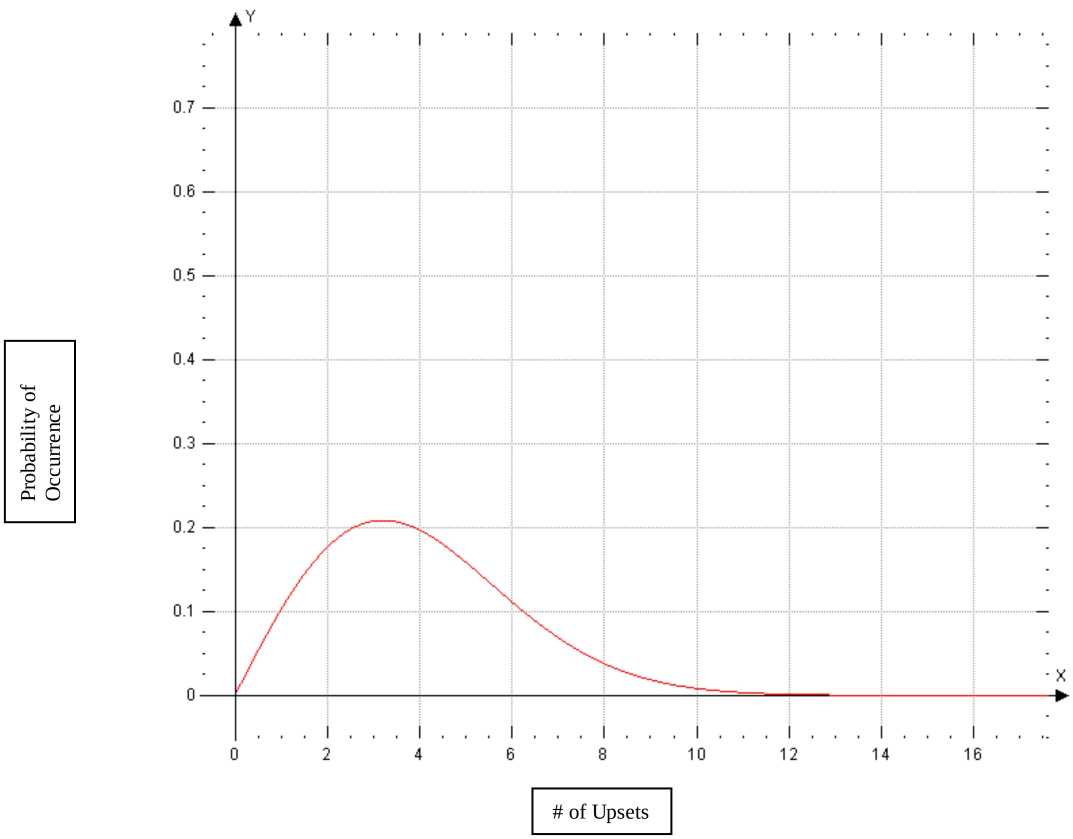

Figure 26. Threat Equation (Rayleigh Distribution)

This graph is termed the threat equation and in the case of Figure 26 follows the equation y = (1.1×(1/(3.2)^2)×exp(-(x^2)/(2×3.2^2))). This notional generalization is based on previous experiments (Vogt-Ardatjew, van de Beek, and Leferink 2014) and is based on the design of the installed component and the magnitudes of the present electric fields.

Generally, as the number of emitters (intentional and unintentional) in the space increase, the likelihood of the installed components experiencing a larger number of

upsets increases. Graphically the threat function will move up and to the right as the electrical field is increased in the enclosed space.

4. Risk Determination

As discussed in the appendix, the resulting function as shown in Figure 27 depicts the overall risk as a function of the square of the number of upsets.

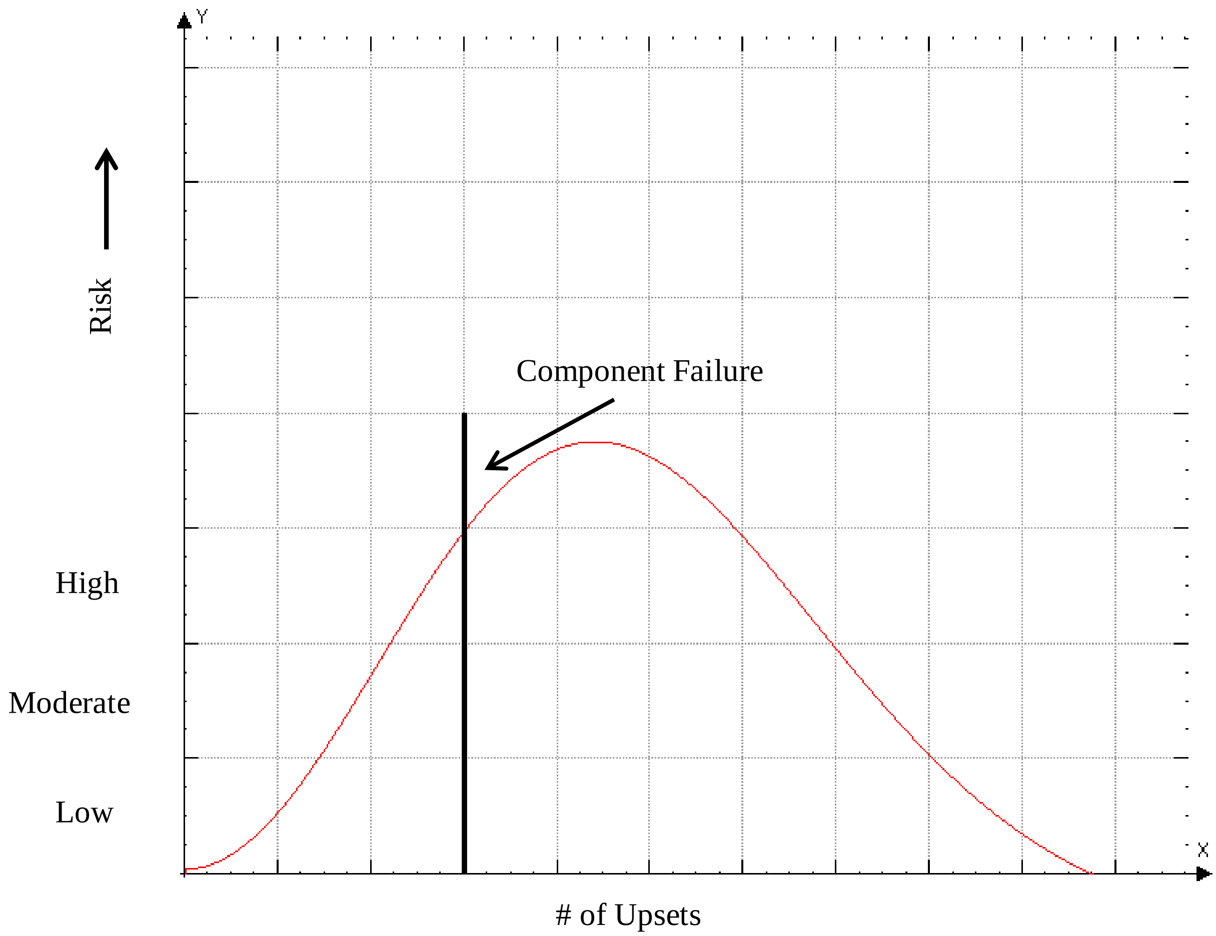

Figure 27. Risk Function

On the y-axis there is a combination of the probability of an upset and the loss expected due to that upset, and the x-axis is in upsets squared which simply a function of this particular risk determination. The classification of risk being low, moderate and high is taken from the familiar DOD Risk Management Guide for Defense Acquisition (DASD Systems Engineering 2014). The y-axis has no units and allows for subjective

qualification dependent on the amount of loss the designer is willing to accept in the loss function development. Furthermore, at some point the electronic upsets in the installed equipment will cause it to fail completely and even though the risk to the component increases the component is no longer affected due to its failure.

The threat function will be dynamic under most operating situations if unintentional emitters enter the space, and this curve is subject to these effects, which leads to another way of interpreting this risk function. If an enclosed space such as the one in the example space above is tested to determine the EM fields incurred with different intentional and unintentional emitter combinations, then it is possible to build a table that represents the risk involved in these combinations by building a risk graph in each case and then applying the graph to the table as shown in Table 1.

	Router 1	Router 1	Router 2	Router 2	Router 3
	Cell 7	Cell 8	Cell 9	Cell 10	Cell 11
	Tablet 0	Tablet 1	Tablet 1	Tablet 2	Tablet 3
High	Router 1	Router 1	Router 2	Router 2	Router 3
	Cell 6	Cell 7	Cell 8	Cell 9	Cell 10
	Tablet 0	Tablet 1	Tablet 1	Tablet 2	Tablet 3
	Router1	Router 1	Router 1	Router 2	Router 3
	Cell 5	Cell 6	Cell 7	Cell 7	Cell 9
	Tablet 0	Tablet 1	Tablet 1	Tablet 2	Tablet 3
	Router 1	Router 1	Router 1	Router 1	Router 3
Moderate	Cell 4	Cell 5	Cell 6	Cell 7	Cell 7
	Tablet 0	Tablet 1	Tablet 1	Tablet 2	Tablet 3
	Router 1	Router 1	Router 1	Router 1	Router 2
	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7
	Tablet 0	Tablet 0	Tablet 1	Tablet 2	Tablet 2
	Router 1	Router 1	Router 1	Router 1	Router 2
	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Low	Tablet 0	Tablet 0	Tablet 1	Tablet 2	Tablet 2
	Router 1	Router 1	Router 1	Router 1	Router 2
	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5
	Tablet 0	Tablet 0	Tablet 1	Tablet 2	Tablet 2

Table 1. Risk Evaluation Table

Again, this type of visual display of information is notional and can be adjusted in accordance with the user's needs. The number and type of emitters is listed in each cell, and as the table moves up and to the right the risk of increasing the number of electronic upsets increases.

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III. CONCLUSION AND SUMMARY

A. CONCLUSION

The desire to include wireless technology in the design of a system or system of systems in order to gain the desired functionality, comprises must be coupled with an understanding of the risks that that same technology introduces into enclosed spaces. There has been a plethora of scholarly effort that shows that EMI in ICs and other susceptible equipment is a concern when they are in the presence of an EM field.

In most civilian systems the risk of EMI is minimized due to its use in large EM field absorbent spaces, the low level EM radiation fields experienced and the criticality of the components placed in these fields. Contrarily, the risk to the installed equipment in the enclosed spaces onboard U.S. Navy vessels is much higher due to the reverberant nature of the enclosed steel spaces, the higher average and peak magnetic fields caused by reverberation and the critical nature of the installed equipment.

This risk determination method offer the engineering team a supplemental risk evaluation method that incorporates qualitative and quantitative information in order to facilitate the a more complete representation of the benefits in light of the possible consequences involved in wireless technologies.

B. FURTHER RECOMMENDATIONS

Modeling the behavior of one electrical component, for example, a transistor in a steady state EM field is computationally possible with the current state of the art software. Building a computer model that accurately depicts multiple electronic components in a dynamic EM field scenario is just not possible. This fact indicates the need to acquire data from complex systems in dynamic EM fields in real world applications. Efforts need to be made to acquire this data and implement it in this and other forms of risk determination. This data could be in the form of component lifetimes, error rates in computational functions, EM field sensors and so on.

A limitation to this thesis was the lack of this data which is necessary to verify the accuracy of the risk determination as outlined in this paper. With the use of actual data to build the appropriate loss functions and Rayleigh distributions, another researcher may be able to further develop this risk determination to more accurately represent real-world in-situ enclosed spaces and therefore provide the necessary risk evaluations needed to assess the use of intentional and unintentional emitters in enclosed spaces onboard U.S. Navy vessels.

Assuming this data remains unavailable, in the near future it may be necessary to severely limit the use of intentional and unintentional emitters in enclosed spaces unless other methods of decreasing the likelihood of EMI are put into place. These methods include increased shielding of installed components and the use of wireless mesh networks.

Increasing the shielding of an installed component increases its overall cost and normally increases its weight. But with recent developments in the use of polyaniline composite plastic that behave as shields and are structurally sound, this problem might be resolved. Some of these composites not only reflect EM radiation, they also absorb part of the radiated energy (Fauveaux and Wojkiewicz 2003).

The other option is to use a mesh network of relatively low power intentional emitters to ensure a signal is available throughout a given space without the need for one high power intentional emitter located at one end of the space that must be powerful enough to provide minimal signal strength to the entire space.

APPENDIX. RISK FUNCTION (LANGFORD 2015)

The likelihood of occurrence is a relation between pairs of propositions, but not necessarily only those that are related to the occurrence (Keynes 1921). The degree of relation may not be well known and therefore the relation to the occurrence must be in the realm of the possible. Probabilities do not suppose causality between the propositions, only the test of correlation is deemed necessary. The test of what is necessary and also that which is sufficient is a higher test of the relation, but as stated previously, may not imply causality in the modal, conditional, or proximate sense for the sine qua non of causes (G. Langford 2012). In the most general sense, the likelihood of occurrence is related to the enactment of functions that carry the potential to satisfy the test of "necessary and sufficient." In other words, this test posits a logical relation between the propositions expressed by one object that interacts with another object that (at a minimum) appears to result in a function that correlates with performance that is measurable. A proposition is represented by each object with its inherent mechanisms. By design, likelihood expresses a belief structure about a proposition and therefore about the role of that proposition while it interacts with another object (and that other object's proposition) in the formation and enactment of the function. Rather than formulating an argument that supports the subjective inclinations of an evaluator of risk, the functional performance that derives from the interaction between two objects is objective and measureable within the arguable positions of measurement theory. What the risk evaluator thinks about the propositions is therefore quantifiable through measures and metrics of functional performances related to various actions and events of the objects within the constructs of their logical relation. The degree (or assessment) of likelihood that a mechanism will perform as indicated by past history or by predictive analysis forms a quantitative basis that increases the objectivity of the propositions that comprise one of the two bases of risk – likelihood that a correlative function is at work and will produce a better or worse situation than is assessed at the time of evaluation. The other basis of risk is that of the consequence of the various enactments of the function. That an event occurs due to the actions of the function is itself sufficient to determine the

consequence of that function. We can know that an event has occurred by analogy with past history and by extrapolating from past history to the present and future time to determine the impacts should the good/bad event occurs. In the tradition of Lowrance (Lowrance 1976) and Lewis (Lewis 2006), simple risk (that is deemed harmful) is a function of threat, vulnerability, and damage (Clemens 2009). The threat results from the objects that interact to enable a function; while the vulnerability and damage relate to the consequences from that threat. Consequence is measurable in terms of energy, matter, material wealth, or information (EMMI) and likelihood is measurable in terms of a number that reflects on the relation between the deleterious events that have occurred in the past or are possible to occur in the future. The assessment of the likelihood of those events occurring varies between 0% and 100%, depending on their assessment on an event scale, and then on a temporal scale that relates the events to past, present, and future time. Therefore, the simple expression of risk as likelihood multiplied by consequence is now expressed through the functional performance of correlative actions derived from mechanisms within objects that interact (and are related to the dire events that have transpired in the past or are predicted to occur in the future.

The expression of functionalized likelihood is captured in a graphical representation in Cartesian coordinates of a mathematical general loss function (G. Langford 2012) as the performance (abscissa), while the consequence is portrayed as a loss (ordinate). Figure 19 depicts the loss function with shape parameter, $n = 2$ (typical of standard production of goods, (Taguchi 1987)).

Simple loss function illustrates the consequences in loss of Energy, Matter, Material Wealth, or Information (EMMI) in terms of the performance measure, e.g., distance.

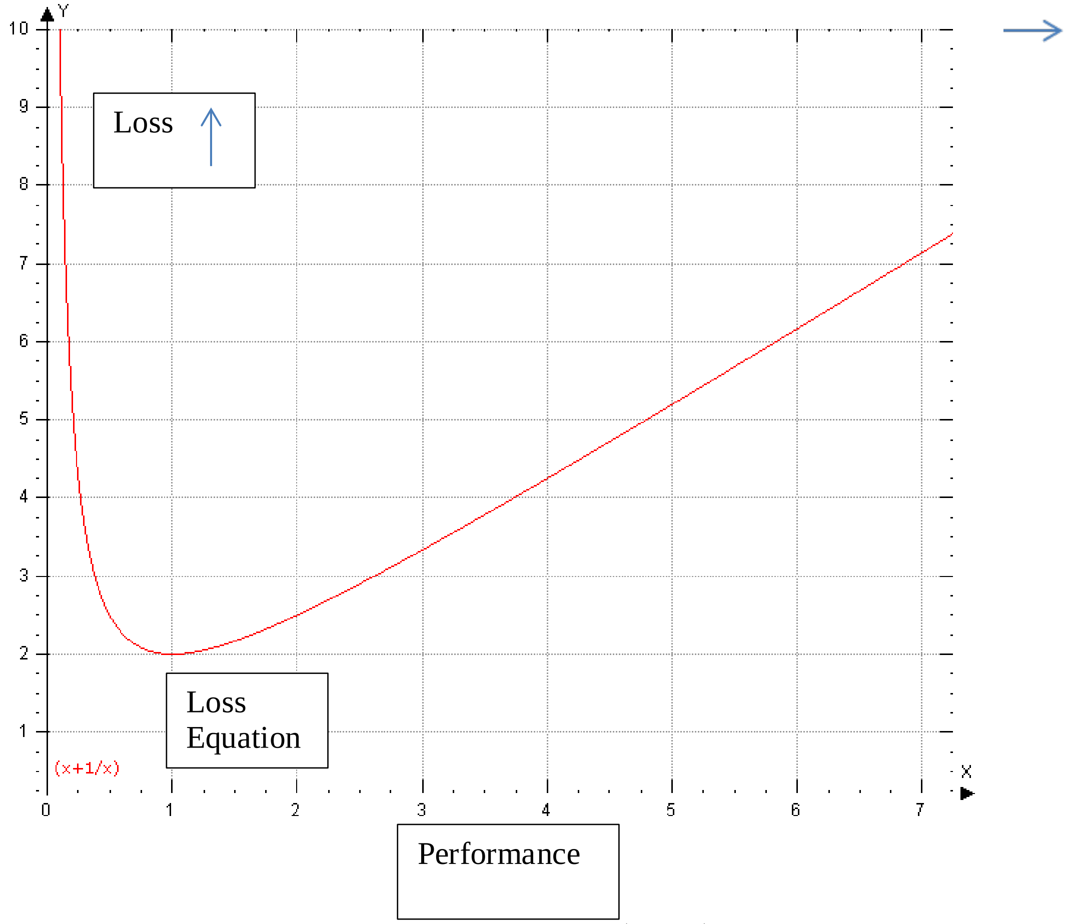

Figure 28. Loss Function (x+1/x)

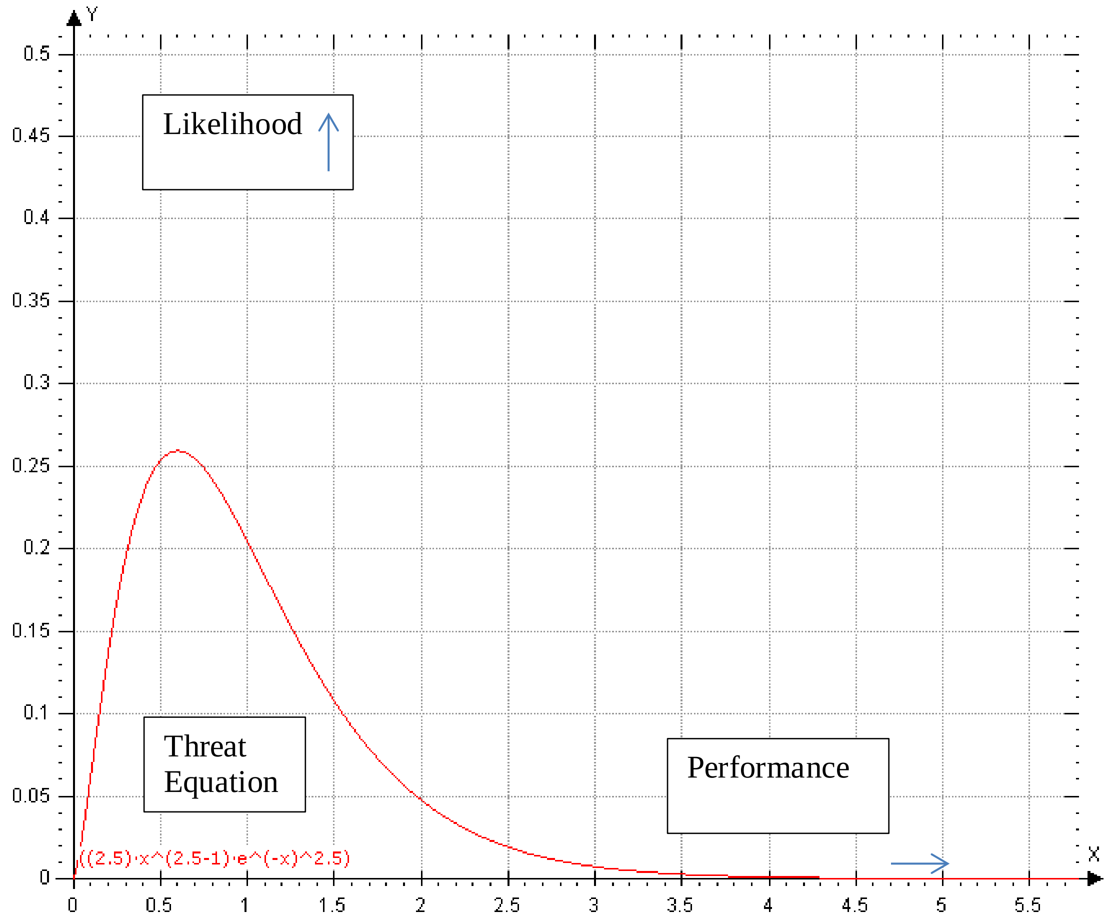

Figure 29. Weibul Distribution with Equation

Weibul function (with shape factor = 2.5) depicts the likelihood of the threat in terms of the performance measure, e.g., distance.

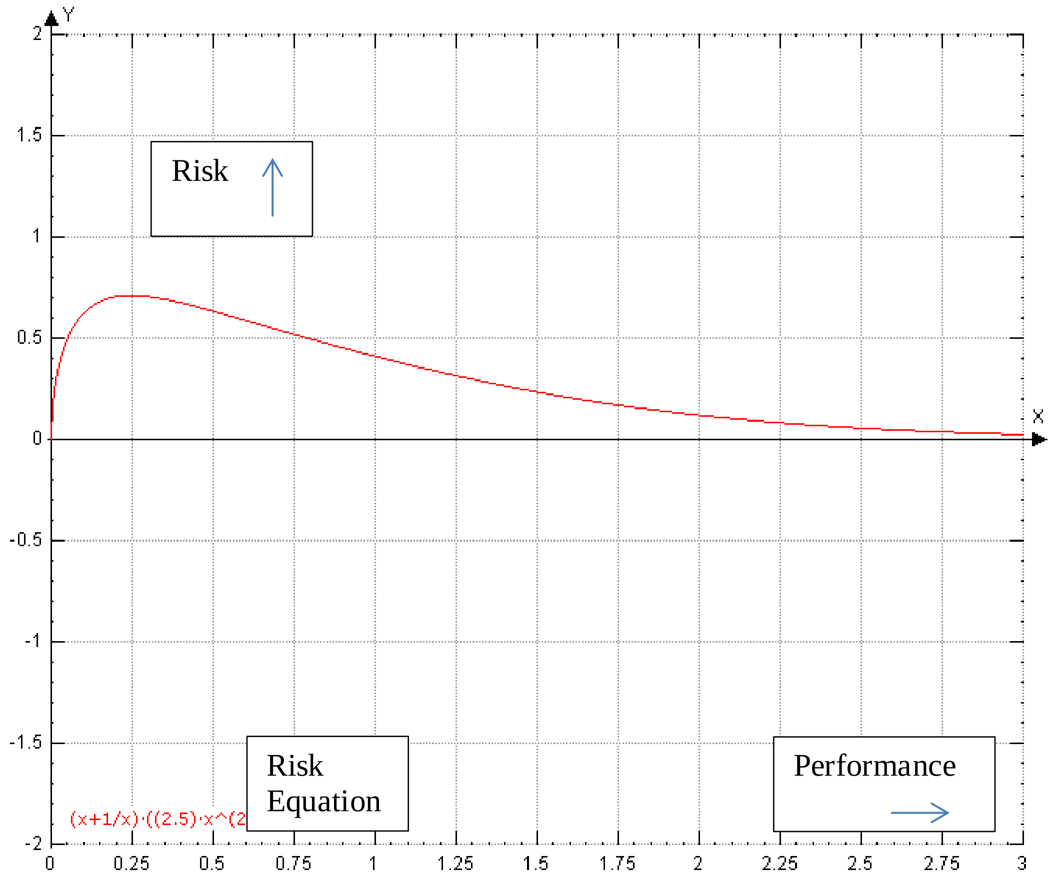

Figure 30. Risk Function

Risk function, the result of multiplying the likelihood times the consequence.

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